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REVISED
REMEDIATION SYSTEM DESIGN AND CORRECTIVE ACTION PLAN

Wheeling Pittsburgh Steel

Plant #1, Martins Ferry, Belmont County Ohio

Incident #0702394-01

GROUNDWATER TECHNOLOGY ®

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April 26, 1995

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1.0 INTRODUCTION

Groundwater Technology, Inc. has been retained by Wheeling-Pittsburgh Steel to design a long-term corrective action to address a gasoline release from an underground storage tank. Based on the information collected from the site during the past investigations and a pilot test, soil vapor extraction and air sparging have been selected as the most effective remediation technologies for this site. The system recommended for this site has been designed specifically to address the areas and lithologies which have been impacted by the gasoline release. Two soil vapor extraction systems have been included in the design because it is not possible to induce air flow through the lower permeability sandy clay soil with a single set of extraction wells.

A Conceptual Remediation System Design for the Wheeling Pittsburgh Steel Corporation was approved by the Ohio Department of Commerce, Division of State Fire Marshal, Bureau of Underground Storage Tank Regulations (BUSTR) on March 11, 1994. A full-scale remedial system design was prepared on June 30, 1994 and was submitted for BUSTR review. This final design incorporates changes suggested by BUSTR and takes into account information collected at the site since June 30, 1994.

1.1 Site Location

Wheeling Pittsburgh Steel Corporation's Martins Ferry Plant #1 (Plant #1) is located within the borough of Martins Ferry, Belmont County, Ohio. The location is further identified on the Wheeling, West Virginia-Ohio, United States Geological Survey, 7.5-Minute Series (Topographic) map as the southwest corner of Section 18, Township 3 North, Range 2 West. A Site Location Map is provided as Figure 1.

The Ohio River is located approximately 200 feet east-southeast of the eastern edge of the facility. A series of eight (8) municipal water wells, operated by the Martins Ferry Municipal Water Authority are located between Plant #1 and the Ohio River. The closest of these wells is approximately 670 feet from a former gasoline underground storage tank located at Plant #1. A Site Area Map and Site Map are presented as Figure 2 and Figure 3, respectively.

1.2 Background Information

The soil and groundwater at Plant 1 has been impacted by a past release of gasoline from an underground storage tank. The Ohio Department of Commerce, Division of State Marshal, Bureau of Underground Storage Tank Regulations (BUSTR) has established regulations which govern the investigation and corrective actions required to address leaking underground storage tanks. These regulations have been promulgated as Revised Ohio Code Sections 3737.87 through 3737.99. The following steps are required to address an apparent release from an underground storage tank:

- Release confirmation;
- Initial corrective action;
- Free product recovery;
- Site assessment; and
- Long-term corrective action.

Wheeling Pittsburgh Steel has confirmed the suspected release, conducted initial corrective actions, performed liquid-phase hydrocarbon removal, and has performed a site assessment activities at the release location. The purpose of this report is to document the design of a soil vapor extraction and air sparging system which has been selected as the long-term corrective measure.

1.3 Summary of Past Investigations and Interim Remedial Measures

In September 1990, Wheeling-Pittsburgh Steel Corporation excavated and removed a 1,000-gallon underground storage tank (UST). The UST was used to store gasoline and was enclosed in a concrete vault. The approximate location of the former UST is presented on Figure 3. During removal of this tank, evidence of a release was observed by Wheeling-Pittsburgh Steel personnel. As a result, several environmental investigations and interim remedial measures have been performed, on behalf of Wheeling-Pittsburgh Steel in the area of the former underground storage tanks. These include:

- Site Assessment;
- Phase II Site Assessment;
- Interim Remedial Measures;

- Remediation System Pilot Testing;
- Additional Site Assessment; and
- Supplemental Assessment (currently in progress).

Provided below is a summary of these investigations.

Site Assessment

In November, 1990, after removal of the underground storage tank, John Mathes and Associates performed a Site Assessment. This assessment included the installation of four groundwater monitoring wells (monitor wells), collection/analysis of soil samples and collection/analysis of groundwater samples. The locations of these monitor wells are presented of Figure 3 (MW-1S through MW-4S). The results of this investigation were documented in a report entitled "Site Assessment Report, Wheeling-Pittsburgh Steel Company, Martins Ferry Site" December 1990, John Mathes Associates.

Phase II Site Assessment

Beginning in May 1991, John Mathes and Associates performed a Phase II Site Assessment. This assessment included a soil vapor survey, installation of 10 monitor wells and a recovery well (RW), collection/analysis of soil samples and collection/analysis of groundwater samples. The locations of these wells are presented on Figure 3 (MW-5S, MW-6D, MW-7S, MW-8S, MW-9D through MW-14D and RW-1). The results of this investigation were documented in a report entitled "Phase II Site Assessment Report, Wheeling-Pittsburgh Steel Company, Martins Ferry Ohio" August 1991, John Mathes Associates.

Interim Remedial Measures

During the Phase II Site Assessment, liquid-phase hydrocarbons were detected wells MW-1S (0.33 feet), MW-6D (0.05 feet), MW-9D (0.01 feet), MW-10D (0.89 feet) and RW-1 (1.30 feet). Interim remedial measures were initiated in June 1991, to recover the liquid-phase hydrocarbons. These measures included installation and operation of petroleum recovery pumps in MW-10D and RW-1. The pumps remained in operation until January 27, 1992 when gauging of the wells indicated the presence of liquid-phase hydrocarbons in only two wells; MW-1S (0.02 feet) and MW-4S (0.01 feet). During the period of these interim measures, monthly product removal reports were prepared and submitted to BUSTR.

Remediation System Pilot Testing

In October and November 1992, Groundwater Technology performed an investigation consisting of additional assessment activities and an air sparge/soil vapor extraction pilot test in the area of MW-6D. The scope of work associated with this investigation included: Installation of three monitor wells (MW-15D, MW-16D and MW-17S); installation of test points necessary to perform the pilot test; performance of slug tests; and performance of the pilot test

The air sparge well was installed in a bore advanced to 52 feet below ground surface. A two-foot long section of two-inch diameter, 0.020-inch, machine slotted PVC well screen was installed at the base of the boring and PVC well casing was extended to ground surface. The annulus of the bore was filled with washed sand until there was approximately six feet of sand above the top of the well screen. A three-foot thick bentonite seal was installed immediately above the sand pack and the remainder of the well bore annulus was filled with cement grout. With this configuration, the top of the well screen and the bottom of the bentonite seal were approximately ten feet and four feet below the water table surface, respectively. The soil vapor extraction well was installed in a bore advanced to 40 feet below ground surface. A fifteen-foot long section of four-inch diameter, 0.040-inch, machine slotted, PVC well screen was installed from 24 to 39 feet below ground surface. A sandpack was placed in the bore annulus until there was approximately five feet of sand pack above the well screen. A three-foot thick interval of bentonite was installed before the remainder of the bore was filled with cement grout.

The soil vapor extraction test was conducted by applying a vacuum to the test well and measuring the resulting soil vapor extraction rate and the vacuum at the subsurface monitoring points. The concentration of volatile organic compounds in the extracted soil vapor was monitored using a field instrument equipped with a flame ionization detector. Three applied vacuum/extraction flow pairs were completed. During the highest applied vacuum a soil vapor sample was collected in a Tedlar bag and submitted for laboratory analysis to determine the concentration of BTEX and gasoline hydrocarbons.

The efficacy of air sparging was evaluated by injecting air into the air sparge well at a measured flow rate and pressure. Groundwater elevation changes, groundwater dissolved oxygen concentration changes and vadose zone pressure changes were monitored as indicators of air movement. Changes in the concentration of volatile organic compounds in the extracted soil vapor was also monitored to show that operation of an air sparge system could increase the rate of hydrocarbon removal from the subsurface.

The results of these tests are summarized in **Table 1**.

TABLE 1
Pilot Test Results

Wheeling-Pittsburgh Steel Corporation
Martins Ferry, Ohio Plant No. 1
November 17 & 18, 1992

Parameter	Air Sparge Test	Soil Vapor Extraction Test[1]
Flow Rate	10 - 15 scfm	50 - 70 scfm
Pressure/Vacuum	10 - 25 psi (pressure)	12 - 18 in. w.c. (vacuum)
Radius of Influence	20 - 40 feet	30 - 50 feet
Initial Hydrocarbon Removal Rate[2]	117 lb/day (combined AS/SVE system)	77 lb/day (SVE system only)

Notes:
[1] The results of the SVE pilot test characterize air flow in the sand and gravel layer. Values necessary to characterize air flow in the sandy clay layer have been assumed based on Groundwater Technology's experience at other sites with similar geologic characteristics.
[2] The initial hydrocarbon removal rate is calculated by multiplying the concentration of petroleum hydrocarbons observed during the test by the test extraction rate it is not indicative of the removal rate expected from the final SVE system(s).

The results of this investigation were documented in a report entitled "Conceptual Remediation System Design and Corrective Action Plan, Wheeling-Pittsburgh Steel Corporation, Plant 1 of the Martins Ferry Facility" April 23, 1993, Groundwater Technology, Inc. The conceptual design presented in the April 1993 report contained a recommendation for 25 soil vapor extraction wells and 18 air sparge wells.

Additional Investigation

After reviewing data collected from the investigations described above, the presences of two water bearing zones in the area of Plant #1 was suspected; a discontinuous perched water table in the area of the former UST and a deeper water bearing zone. In September 1993, Groundwater Technology performed an investigation to determine if two water bearing zones exist at the site. This investigation included the installation of one monitor well (MW-8D) adjacent to MW-8S. The results of this investigation which confirmed the presence of two water bearing zones were documented in a report entitled "Additional Investigation Report for

Wheeling-Pittsburgh Steel Corporation, Plant 1 of the Martins Ferry Facility" October 29, 1993, Groundwater Technology, Inc. This conceptual design was approved during March 1994.

Supplemental Assessment (currently in progress)

In July 1994, Groundwater Technology initiated Supplemental Assessment activities at the site. These activities include(d):

- A monthly program to gauge the monitor wells and, if present, bail liquid-phase hydrocarbons;
- Collection of groundwater samples from 11 on-site monitor wells;
- Resurveying the tops-of-casing locations and elevations (relative to mean sea level) of the on-site monitor wells and municipal water wells;
- Establishment of a fixed gauging point to monitor river pool elevation;
- Preparation of a groundwater flow model to aid in the selection of locations for additional "point-of-compliance" wells;
- Installation of two additional "point-of-compliance" wells to be located between the facility and the municipal wells; and
- Quarterly groundwater sampling from the two additional monitor wells, MW-8D, MW-8S and MW-16D.

As of the date of this report, Groundwater Technology is continuing the monitor well gauging and bailing program. The monitor wells and municipal wells have been surveyed and a fixed river gauge has been established. This information has been used to prepare revised site maps (Figure 2 and Figure 3). The groundwater flow model is currently being prepared.

1.4 Site Geology/Hydrogeology

The soils at the site consist of fill material underlain by a generally downward coarsening sequence of fluvial deposits. A perched water bearing zone was identified in the area of the former UST. The areal extent of this perched zone is unknown, but appears to be present in the southern portion of the investigation area (identified in monitor wells MW-1S through MW-5S, MW-7S, MW-8S and MW-17S) and appears to pinch-out between MW-1S and MW-6D. The native soils within the perched zone consist of clays and sandy clays. Beneath the perched water bearing zone, a deeper aquifer, consisting of sands and gravels was identified.

Depths to water in the area of perched water bearing zone ranges from approximately 19 to 26 feet below surface grade with fluctuations as great as 5 feet (low to high water table conditions). Depths to water in the deeper water bearing zone ranges from approximately 28 to 43 feet below surface grade with fluctuations as great as 8 feet (low to high water table conditions). Groundwater elevation contour maps for both water bearing zones are presented as Figure 4 and Figure 5.

1.5 Distribution of Contaminants

Historically liquid-phase hydrocarbons had been detected floating on the water table periodically in six wells: MW-1, MW-4, MW-6, MW-9, MW-10, and RW-1. Recent gauging of the monitor wells has indicated the presence of liquid-phase hydrocarbons in MW-6D and MW-10D, with thickness ranging from 0.01 to 0.02 (MW-6D) and 0.01 to 0.05 (MW-10D).

The distribution of adsorbed phase hydrocarbons (TPH) within the area of the perched water bearing zone (26-30 feet below surface grade) is presented on Figure 6. The distribution of adsorbed-phase hydrocarbons (TPH) within the deeper water bearing zone (34 to 38 feet below surface grade is presented on Figure 7.

Figure 8 and Figure 9 presents the distribution of dissolved-phase hydrocarbons in the perched water bearing zone and the deeper water bearing zone, respectively. These maps were based on the most recent groundwater analyses (December 20, 1994).

1.6 State Fire Marshall Site Feature Scoring System

The State Fire Marshall Site Feature Scoring System (SFSS) chart was used to determine action levels for the soil and groundwater at the site. This system utilizes a spreadsheet to categorize a site based on locations of potable wells, depth to groundwater, predominant soil type, and natural and/or man-made conduits or receptors. A copy of the completed SFSS chart is presented in Appendix A. This UST site is classified as a Category 3 site (a score of 55 was calculated using the SFSS). The action levels for a Category 3 site are:

- Soil BTEX: 0.335/9/14/67 (mg/kg);
- Groundwater BTEX: 0.005/1/0.700/10 (mg/L); and
- Soil TPH (Gasoline): 450 mg/kg.

2.0 SITE EVALUATION AND SYSTEM DESIGN PROCESS

To begin the design process for a long-term remediation strategy for the site, Groundwater Technology reviewed the data which had been collected at the site, reviewed the Category 3 SFSS action levels and established the following remediation goals:

- Remove the petroleum hydrocarbons adsorbed to soil in the sandy clay in the area near the former gasoline storage tank;
- Remove the petroleum hydrocarbons adsorbed to soil in the sand and gravel layer down gradient (northwest) of the former storage tank area; and
- Provide a mechanism to enhance the removal of petroleum hydrocarbons from the groundwater.

Although the pilot study did not conclusively define air flow through the sandy clay layer, it did indicate that air sparging and soil vapor extraction could effectively be applied to remove volatile organic compounds from the groundwater and from soil in the sand and gravel layer. Based on Groundwater Technology's extensive experience with air sparging and soil vapor extraction, the following assumptions were used to fill gaps in the site assessment and pilot study data:

- Gasoline released from the former UST migrated along the sand clay layer in a northwesterly direction toward MW-6 (approximately 150 feet);
- Petroleum hydrocarbons adsorbed to soil in the sandy clay layer is limited to a width of approximately 100 feet (measured perpendicular to the northwesterly migration direction);
- The sandy clay layer acted as a barrier to vertical migration and the sand and gravel layer and groundwater within the sand and gravel is not impacted;
- Although perched water has been identified above the sandy clay layer it will not preclude soil vapor extraction in this unit;
- The sand and gravel layer is impacted at MW-6 and RW-1 (it is likely that gasoline migrated vertically into the sand and gravel in this area as the sandy clay layer pinches out near MW-6);
- Groundwater is impacted with petroleum hydrocarbons in an area bounded by MW-6 to the southeast, MW-12 to the southwest, MW-10 to the northwest, and MW-9 to the northeast;

- An air sparge ROI of 40 feet can be achieved by improving the design of the air sparge well (the observed ROI during the pilot test ranged from 20 to 40 feet when injecting air into a well which was not designed to maximize the ROI);

- A conservative slope ($\log_{10}$ pressure vs. distance) of 0.08 can be assumed to describe the attenuation of vacuum in the sandy clay layer (this value is based on Groundwater Technology's experience at sites with similar geologic characteristics and was not developed from data collected during the pilot study conducted at this site);

- The flow / vacuum response model input was set so that an applied extraction well vacuum of 150 inches of water column would result in an extraction rate of 20 standard cubic feet of soil vapor per minute (this value is based on Groundwater Technology's experience at sites with similar geologic characteristics and was not developed from data collected during the pilot study conducted at this site); and

- The concentration of hydrocarbons in the soil vapor extracted from both the shallow and the deep soil vapor extraction systems will decrease rapidly during the startup period and vapor phase activated carbon adsorption will be the most cost effective air treatment alternative.

2.1 Estimate of SVE Effective Radius of Influence

In a conventional SVE pilot test, a vacuum is applied to a well screened through a portion of the vadose zone. The vacuum and total resulting flow are measured at the wellhead, and vacuum in the vadose zone is measured in monitoring points located various distances and directions from the vapor extraction well. The log of the vacuum observed in the monitoring points is routinely plotted against distance from the vapor extraction well, usually giving a line which intercepts the y-axis at 10% to 30% of the applied vacuum. Linear regression analysis is applied to determine the best fit of the data, and the radius of influence is determined by extrapolating the line to an arbitrary vacuum level, usually ranging between 0.01 and 1 inches of water column. The arbitrary vacuum level is significant only because it indicates that there is a pressure gradient in the subsurface which should induce subsurface air flow toward the well. The vacuum itself is not important.

This purely empirical procedure has been widely used and has frequently produced effective SVE system design parameters. However, it does not take into account a number of elements which are known to significantly affect SVE system performance, including requirements for remediation time and net reduction of contaminants adsorbed to soil, contaminant volatility and biodegradability, soil vapor extraction rate, and soil temperature.

To design soil vapor extraction systems, Groundwater Technology uses VENT-ROI, a design tool which provides an estimate of the effective cleanup radius[1] for SVE systems, based on field data readily available from conventional SVE pilot tests. Since 1992, Groundwater Technology, Inc. has been using this model routinely as a design tool for SVE systems.

VENT-ROI assumes that the subsurface is laterally uniform and anisotropic, although the ratio of horizontal-to-vertical permeability may vary. Air infiltration through the ground surface is assumed to be proportional to the subsurface vacuum, which is approximated as dissipating exponentially with distance from the vapor extraction well. Contaminants are assumed to equilibrate between the soil and the gas flowing through the subsurface, with the equilibrium soil gas concentration proportional to soil concentration. Biodegradation is assumed to follow Michaelis-Menten kinetics (zero order at high substrate concentrations, first order at low concentrations) in all areas where oxygen flux to the subsurface significantly exceeds the stoichiometric requirements of the zero order biodegradation rate.

The effective radius, calculated employing these assumptions, is the distance from the vapor extraction well at which subsurface air flow is just sufficient to achieve the remediation goals. It is specific to the desired remediation time, required extent of remediation, and site contaminant. Since air flow is greater between the edge of the contamination plume and a vapor extraction well than it is between two vapor extraction wells, the values for effective radius in these two cases differ and must be calculated separately.

Additional detailed information including several technical papers prepared to support the use and development of VENT-ROI are included in Appendix A.

2.2 Estimate of Air Sparge Radius of Influence

The air sparge radius of influence is defined at the maximum radial distance from the air sparge well where, after traveling through the saturated zone soils, the air exits the saturated zone and enters the vadose zone. Groundwater Technology employs an empirical approach to determine the air sparge radius of influence. This empirical approach relies on observation of one or more of the following:

- The groundwater elevation within the radius of influence will increase during the pilot test as water is displaced by air moving through the saturated zone;

[1] Effective radius is defined as "the maximum distance from a vapor extraction point through which sufficient air is drawn to remove the required fraction of contamination in the desired time".

- Dissolved oxygen concentrations in groundwater will increase within the radius of influence as oxygen supplied by the injected air dissolves into the groundwater; and

- Vadose zone pressures will change indicating that a pressure gradient has been created by air entering the vadose zone.

3.0 DESIGN BASIS

Impacts resulting from the gasoline release are present in three different zones: a relatively low permeability sandy clay layer; an unsaturated sand and gravel layer; and the saturated portion of the sand and gravel layer. To address these three zones of impact, Groundwater Technology recommends installation and operation of a system designed to incorporate two soil vapor extraction systems and an air sparging system. The design basis for each of these systems is shown in Table 2 and is discussed in the following sections.

TABLE 2
Design Basis

Soil Vapor Extraction and Air Sparge Systems
Wheeling-Pittsburgh Steel Corporation
Martins Ferry, Ohio Plant No. 1

Parameter	Shallow Soil Vapor Extraction System	Deep Soil Vapor Extraction System	Air Sparge System
length of impacted zone	150 feet	250 feet	240 feet
average width of impacted zone	100 feet	180 feet	180 feet
average thickness of impacted zone	10 to 15 feet	4 to 5 feet	10 feet
desired soil clean-up time[1]	1 year	1 year	na
net contaminant reduction desired[1]	90 %	90 %	na

Notes:
[1] Desired soil clean-up time and net contaminant reduction are inputs into the VENT-ROI program. The actual clean-up time and net contaminant reduction are a function of many factors including water table fluctuations and the homogeneity of the subsurface soil units. The actual time required to meet the clean-up objective may differ from the program input.

3.1 Shallow Soil Vapor Extraction System for the Sandy Clay Lithology

Removal of gasoline adsorbed to soil in this source area is the objective of the shallow soil vapor extraction system. To design the system Groundwater Technology used VENT-ROI. The data inputs required to execute the VENT-ROI model include:

- The slope of a line plotted to describe the attenuation of vacuum ($\log_{10}$ of pressure) with increasing distance from the extraction well;
- The extraction rate induced when a vacuum is applied to the extraction well;
- The thickness of the vented interval;
- The depth to the top of the vented interval;
- The contaminant adsorbed to the soil; and
- The concentration of the contaminant adsorbed to the soil.

The first two parameters, the vacuum attenuation and the flow / vacuum response, are usually collected during a site specific pilot study. The screened interval is selected, and the thickness of the vented interval determined by analysis of the site well logs. The contaminant characteristics and soil concentrations are determined by laboratory analysis. Because the extraction well used to conduct the pilot study at this site was screened across both the sandy clay and the sand and gravel layers, the flow / vacuum response in the sandy clay was not characterized during the pilot study. To supplement the data collected at the site, Groundwater Technology used the results of other pilot studies conducted in similar soils for input into the Vent-ROI model.

A conservative slope ($\log_{10}$ pressure vs. distance) of 0.08 was used. This slope is characteristic of a relatively low permeability sandy clay soil. The flow / vacuum response model input was set so that an applied extraction well vacuum of 150 inches of water column would result in an extraction rate of 20 standard cubic feet of soil vapor per minute. The thickness of the vented interval was determined to average ten feet thick and the screened interval was selected to correspond to this interval. The contaminant selected for evaluation was weathered gasoline. Selection of weathered gasoline in the evaluation is conservative in that not all of the adsorbed gasoline is considered volatile. However, VENT-ROI does recognize that much of the low volatility/high molecular weight compounds which do not volatilize will readily biodegrade as a result of the oxygen introduced to flow into the impacted zone by the soil vapor extraction system.

The Vent-ROI model indicates that the interwell effective radius (the radius from each extraction well where the arbitrary cleanup criteria of 90 percent removal in one year will be satisfied) is slightly greater than eighteen feet when volatilization and biodegradation is considered and the soil vapor extraction rate is 20 scfm per well. Using this effective radius, a system was designed to include thirteen wells arranged in a seven by two hexagonal array. The spacing between each well in the array is 31 feet to provide approximately 15 percent conservatism. The reduced well spacing was included to compensate for the uncertainty in the assumed design values. The wells in the shallow soil vapor extraction system array are labeled SVE-1 through SVE-13 as shown on Drawing Y1. The array extends approximately 150 feet from MW-3 in the southeast to MW-6 in the northwest. These wells should remove the gasoline hydrocarbons adsorbed to soil in the sandy clay lithology providing effective source reduction.

<u>Shallow Soil Vapor System Design Contingency</u>
A unit of perched water has been observed above the sandy clay unit. At this time Groundwater Technology believes that soil vapor extraction will be effective. However, a design contingency has been included so that if accumulation of water in the shallow soil vapor extraction wells and subsequent entrainment and collection in the blower moisture separator becomes problematic the situation can be addressed without major modifications to the system.

A 3/8-inch inside diameter, rigid wall, tube will be inserted into each shallow soil vapor extraction well and will extend back to the shallow system piping manifold. At the manifold each tube will extend through a PVC wye fitting where a rubber plug will ensure an air-tight seal between the fitting and the tubing. If water accumulation becomes problematic, a tubing manifold could be constructed and one or more pumps would be used to extract water from the shallow soil vapor extraction wells. Extraction water piping and electrical conduit will be installed between the blower equipment compound and the shallow system piping manifold enclosure. The extracted water would be pumped to the blower equipment compound to be treated and discharged or stored for subsequent disposal.

3.2 Deep Soil Vapor Extraction System for the Sand/Gravel Lithology

Removal of gasoline which has become adsorbed to the sand and gravel soils as a result of the floating non-aqueous gasoline is the primary objective the soil vapor extraction system designed for this lower lithology. The second objective of this system is to capture the vapors liberated by the air sparge system which will be described in detail in Section 3.3 of this report.

The pilot study data indicated that the sand and gravel layer, as expected, is permeable and air can easily be induced to flow through this layer. The test also indicated that flow is mainly horizontal through this layer as there is only gradual attenuation of vacuum with increasing distance from the extraction well.

The average slope (log10 P vs. distance) of a plot of the pilot study vacuum attenuation data, 0.023 per foot, was input into the Vent-ROI model. This slope is characteristic of a relatively high permeability sand and gravel soil. The flow / vacuum response indicated that an applied extraction well vacuum of 18 inches of water column would result in an extraction rate of approximately 70 standard cubic feet of soil vapor per minute. The thickness of the vented interval was determined to average five feet thick and the screened interval was selected to correspond to this thickness. The contaminant selected for evaluation was weathered gasoline. Again selection of weathered gasoline in the evaluation is conservative.

The Vent-ROI model indicates that the interwell effective radius (the radius from each extraction well where the cleanup criteria of 90 percent removal in one year will be satisfied) is greater than fifty two feet when volatilization and biodegradation is considered. Using this effective radius a system was designed to include seven extraction wells spaced approximately 90 feet apart. These wells are labeled SVE-14 through SVE-20 as shown on Drawing Y3. The array extends approximately 250 feet from south to north and approximately 180 feet from east to west. The deep soil vapor extraction well array is centered between wells MW-1 and RW-1.

These wells will remove the gasoline hydrocarbons adsorbed to soil in the sand and gravel lithology providing effective source reduction. In addition, it is expected that much of the soil vapor extracted by the interior wells will be supplied by the air sparge system. The exterior wells will therefore be forced to draw air from the perimeter of the soil vapor extraction well array. Since the pilot study has shown that flow is largely horizontal in this regime, this will result in effective capture of vapors liberated by the air sparge system and should extend the actual sparge air capture zone well beyond the effective radius predicted by VENT-ROI. In addition, the well spacing is approximately 15 percent more conservative than the VENT-ROI model output suggests, to minimize the chance for sparge air escaping capture by the deep soil vapor extraction system.

3.3 Air Sparge System

Based on the results of the pilot study conducted during November 1992, Groundwater Technology recommends installation of a multi-point air sparging system in the area where elevated concentrations of BTEX have been detected in the groundwater. The sparge system has been designed to address impacted groundwater north, west and northeast of RW-1. The sparge point array extends 240 feet from south to north and 180 feet from east to west. The distribution of dissolved BTEX and TPH concentrations for the lower saturated zone are shown on Figure 9. The effectiveness of the sparge system as a groundwater clean-up tool will extend well beyond the reported radius of influence. This will be due to an increase in the rate of biological decay of the hydrocarbons as a result of the increase in dissolved oxygen in the groundwater.

The observed radius of influence of the air sparge pilot test was twenty to forty feet. Groundwater Technology believes that a radius of influence of at least forty feet can be ensured by making a few simple changes in the construction of the sparge system air injection wells. To enhance the effectiveness of these wells, each well will be installed in borings advanced to 50 feet below ground surface. A one and one-quarter inch diameter galvanized steel well point with two feet of exposed 60 mesh screen will be installed at the base of this boring. Sand pack will be installed to completely cover the well screen however, it will not extend more than one-foot above the screen. A three-foot thick bentonite seal will be installed immediately above the sand pack (the test well had sand pack six feet above the well screen) and the remainder of the annulus of the bore will be filled with a cement/bentonite grout. This change will force the sparge air into the formation approximately five feet deeper than the well used in the pilot study test which should result in a greater radius of influence.

The interior sparge air injection wells have been installed at the center of a triangle formed by the three closest soil vapor extraction wells to ensure complete capture of the vapors liberated by the air sparge system. Each well is within 65 feet of another sparge well which is more than 20 percent conservative considering the expected radius of influence is at least 40 feet. In addition, the regular orientation of the sparge wells will allow uniform air flow through the unsaturated zone of the sand and gravel unit ensuring that these soils are effectively remediated by the soil vapor extraction system.

The outer sparge wells are located beyond the soil vapor extraction well array. However, the deep soil vapor extraction system will capture the sparge air because, as discussed earlier, air flow will be predominantly horizontal in this unit toward the extraction well array.

TABLE 3
Design Summary

Soil Vapor Extraction and Air Sparge Systems
Wheeling-Pittsburgh Steel Corporation
Martins Ferry, Ohio Plant No. 1

Parameter	Shallow Soil Vapor Extraction System	Deep Soil Vapor Extraction System	Air Sparge System
screened interval	18 to 28 feet BGS	32 to 37 feet BGS	48 to 50 feet BGS
screen size/sand pack size	0.040 inch machine slotted / # 00 Jessie Morrie sand	0.040 inch machine slotted / #2 Jessie Morrie sand	60 gauge mesh / # 2 Jessie Morrie sand
well head vacuum/ pressure	150 inches w.c. (vacuum)	18 inches w.c. (vacuum)	15 psi (pressure)
number of wells	13	7	10
flow per well	17.4 scfm	67 scfm	15 scfm
desired soil clean-up time[1]	1 year	1 year	na
net contaminant reduction desired[1]	90 %	90 %	na
interwell effective radius of influence[2]	18.2 feet	52.5 feet	40 plus feet

Notes:

[1] Desired soil clean-up time and net contaminant reduction are inputs into the VENT-ROI program. The actual clean-up time and net contaminant reduction are a function of many factors including water table fluctuations and the homogeneity of the subsurface soil units. The actual time required to meet the clean-up objective may differ from the program input.

[2] Effective radius of influence applies only to the soil vapor extraction wells. The radius of influence for the air sparge system has been determined empirically.

3.4 Air Treatment System

During the soil vapor extraction and air sparge pilot study, soil vapor samples were collected for laboratory analysis. The results of these analyses are presented in Table 4.

TABLE 4
Soil Vapor Sample Analysis[1]

Wheeling-Pittsburgh Steel Corporation
Martins Ferry, Ohio Plant No. 1
November 17 & 18, 1992

Analyte	SVE Test Result (ppb_v)	SVE/ASP Test Result (ppb_v)
benzene	41	69
toluene	94	200
ethylbenzene	19	35
xylenes	82	170
total BTEX	240	470
misc. aliphatics	16000	18000
misc. aromatics	160	250
total hydrocarbons	16000	19000

Notes:

[1] Soil vapor samples analyzed for BTEX and gasoline hydrocarbons using modified EPA Method T03.

Evaluation of the petroleum hydrocarbon concentrations in the soil vapor initially indicates that a thermal or catalytic oxidation process is required to provide cost-effective treatment of the long-term system. However, it is important to note that the soil vapor contained mostly aliphatic compounds. These compounds are typically low molecular weight / highly volatile compounds. They are usually present in high concentrations in samples collected during pilot studies but the concentrations usually decline rapidly during the first several days or weeks of full-scale system operation. Based on this experience with soil vapor extraction system operation, Groundwater

Technology evaluated the concentration of BTEX and other miscellaneous aromatics in the soil vapor. Gac-Use, an internal computer model which predicts activated carbon usage based on isotherm developed by Michigan State University, was used to predict activated carbon usage rates for the site. The model predicted less than one ton of carbon per year when only the concentration of BTEX compounds was input and slightly more than one ton when it was assumed that the miscellaneous aromatics would adsorb in a manner similar to benzene.

The transient start-up condition in which aliphatic compounds will be present in the soil vapor will result in higher carbon usage rates during this period. Gas fired and electrically heated catalytic oxidation units as well as activated carbon adsorbers were considered for use at this site. However, the concentrations of aliphatic compounds will not persist long enough to warrant additional cost/benefit analyses between activated carbon and thermal/ catalytic processes. Groundwater Technology believes that activated carbon will provide cost-effective removal of the petroleum hydrocarbons from the soil vapor stream.

The actual initial influent concentrations and the decrease of these concentrations with time are impossible to predict for a system with as many extraction and air sparging wells as the proposed system. Groundwater Technology anticipates that the initial charge of activated carbon (one ton) will be exhausted with the first month or two of operation. As a result, field monitoring of the effluent concentration from these adsorbers should be conducted to determine when a change out is required. To assist in prediction of activated carbon exhaustion rate, Groundwater Technology recommends collection of a soil vapor sample from the inlet to the adsorbers for laboratory analysis. Once the inlet concentrations are known activated carbon isotherms will be used to predict the approximate online time which can be expected for each adsorber.

4.0 SYSTEM DESIGN

The following sections describe in detail the design of the deep and shallow soil vapor extraction systems as well as the air sparge system. Additional detail is provided on the engineering drawings included with this report.

4.1 Deep Soil Vapor Extraction System

The layout, well construction and well head piping details of the deep soil vapor extraction system are shown on Drawing Y3.

4.1.1 Well Design

Four-inch diameter, 0.040-inch machine slotted, PVC well screen and PVC well casing will be used to construct the deep extraction wells. Each well will be installed in a 8.25-inch diameter boring installed to approximately 37 feet below ground surface. However, adjustment to the depth of the boring will be made in order to locate the screen within the sand and gravel and above the seasonal high water table. A five foot long section of screen will be installed at the base of the boring and the casing will be extended to ground surface. The annular space around the screen will be filled with Jessie Morrie # 2, or equivalent, washed sand. A three foot thick bentonite seal will be installed in the annulus immediately above the screen and sand pack. The remainder of the boring will be filled with a cement/bentonite grout to grade.

4.1.2 Piping Network

A tee fitting will connect the soil vapor extraction well to the extraction blower through four inch-diameter, schedule 40, PVC pipe. The piping for all wells located outside the existing building will be installed in a below grade trench. The pipe will be sloped toward the extraction well at a 0.5% grade to minimize moisture entrainment. The pipe will rise above grade at the east side of the existing building and will penetrate through the building wall. A four inch diameter butterfly valve for flow control and a pressure gauge will be installed in the piping before each of the wells are manifolded to the suction side of the extraction blower. Similarly the soil vapor extraction wells installed inside the existing building will be piped to the blower manifold using four-inch diameter schedule 80 PVC pipe. This pipe will be routed overhead and will be supported on hangers installed at the building "I" beam support columns.

4.1.3 Extraction Blower

The extraction blower for the deep soil vapor extraction system must be capable of moving 675 standard cubic feet per minute of soil vapor at a vacuum of 18 inches of water column. The blower selected for this application is a positive displacement blower manufactured by Spencer Turbine (or equivalent). The blower is equipped with a 7.5 horsepower explosion-proof motor energized by 460 volt, three-phase electric power.

The blower assembly will be equipped with an inlet moisture separator equipped with a high water level shutdown and with inlet and outlet silencers. This skid-mounted, belt-driven system will be equipped with guards which comply with OSHA requirements.

4.2 Shallow Soil Vapor Extraction System

The layout, well construction and well head piping details of the shallow soil vapor extraction system are shown on Drawing Y4.

4.2.1 Well Design

Two-inch diameter, 0.020-inch machine slotted, PVC well screen and PVC well casing will be used to construct the shallow extraction wells. Each well will be installed in a 6.25-inch diameter boring installed to approximately 28 feet below ground surface. However, adjustment to the depth of the boring may be made in order to locate the screen within the sandy clay zone above the sand and gravel unit. A ten-foot long section of screen will be installed at the base of the boring and the casing will be extended to ground surface. The annular space around the screen will be filled with Jessie Morrie # 00, or equivalent, washed sand. A three-foot thick bentonite seal will be installed in the annulus one foot above the screened interval. The remainder of the boring will be filled with a cement/bentonite grout to grade.

4.2.2 Piping Network

A tee fitting will connect the soil vapor extraction well to the extraction manifold through a two inch-diameter, schedule 40, PVC pipe. The piping will be installed in a below grade trench and the pipe will be sloped toward the extraction well at a 0.5% grade. The extraction manifold will be located in an above ground "dog house" structure near MW-1. A two-inch diameter butterfly valve for flow control and a pressure gauge will be installed in the piping before each of the wells connect to the manifold. The manifold will be connected to the extraction blower through a four inch-diameter, schedule 40, PVC pipe. The pipe will rise above grade at the east side of the existing building and will penetrate through the building wall. The piping network has been designed to limit the friction loss to less than 6-inches of water column between any shallow well and the extraction blower. Construction details for the piping system are shown on Drawings Y5 and Y6.

As discussed in Section 3.1.1, 3/8-inch diameter tubing will be inserted into each shallow soil vapor extraction well extending back to piping manifold, to extract water from the perched water table if necessary. The tubing will be capped at the extraction manifold for future use. A two inch-diameter, schedule 40 PVC, water discharge pipe and two, one inch-diameter electrical conduits will be installed between the blower equipment compound and the shallow system piping manifold enclosure.

4.2.3 Extraction Blower

The extraction blower for the shallow soil vapor extraction system must be capable of moving 240 standard cubic feet per minute of soil vapor at a vacuum of 150 inches of water column. The blower selected for this application is a positive displacement blower manufactured by Spencer Turbine (or equivalent). The blower is equipped with a 15 horsepower explosion-proof motor energized by 460 volt, three-phase electric power.

The blower assembly will be manufactured with an inlet moisture separator equipped with a high water level shutdown. Inlet and outlet silencers will be provided to minimize noise. This skid-mounted, belt-driven system will be equipped with guards which comply with OSHA requirements.

4.3 Air Sparge System

The layout, well construction and well head piping details of the air sparge system are shown on Drawing Y2.

4.3.1 Well Design

A one and one quarter-inch diameter, galvanized steel well point and galvanized steel pipe will be used to construct the air sparge wells. Each well will be installed in a 6.25-inch diameter boring installed to approximately 50 feet below ground surface. However, adjustment to the depth of the boring may be made in order to locate the screen within the sand and gravel zone a minimum of ten feet below the average water table elevation. The well point which is constructed with a two-foot long section of 60 mesh screen will be installed at the base of the boring and the casing will be extended to ground surface. The annular space around the screen will be filled with Jessie Morrie # 2, or equivalent, washed sand. A three foot thick bentonite seal will be installed in the annulus one foot above the screened interval. The remainder of the boring will be filled with a cement/bentonite grout to grade.

4.3.2 Piping Network

A tee fitting and a two-inch, galvanized steel pipe will connect each air sparge well to the manifold located in the treatment area. The piping for all wells located outside the building will be installed in a below grade trench. The piping will rise above grade at the east side of the existing building and will penetrate through the building wall. A two-inch diameter butterfly valve for flow control and a pressure gauge will be installed in the piping before the manifold at the pressure side of the blower. Similarly the sparge wells installed inside the building will be piped to the blower manifold using a two inch-diameter galvanized steel pipe. This pipe will be routed overhead and will be supported on hangers installed at the building "I" beam support columns. Construction details for the piping systems are shown in Drawings Y2 and Y6.

4.3.3 Air Injection Blower

The blower for the air sparge system must be capable of moving 240 standard cubic feet per minute of compressed air at a pressure of 16 psig. The unit selected for this application is a duplex unit which consist of two blowers arranged in series. Both blowers are positive displacement models manufactured by Spencer Turbine (or equivalent). The blower is equipped with one, 25 horsepower explosion-proof motor energized by 460 volt, three-phase electric power.

The blower assembly will be manufactured with an inlet and outlet silencers to minimize noise. An interlock will be provided to allow operation of the sparge blower only when the deep soil vapor extraction system is operational. This skid-mounted, belt-driven system will be equipped with guards which comply with OSHA requirements.

4.4 Air Treatment

Activated carbon adsorption is recommended to removed gasoline constituents from the soil vapor extracted from the shallow and deep soil vapor systems. Adequate contact time, and even distribution of air flow through the beds are critical to the design of a vapor phase activated carbon adsorption system. Groundwater Technology recommends installation of two Ventsorb units manufactured by Calgon Corporation. Each of these vessels will contain 1,000 pounds for granular activated carbon and the adsorption vessels will be equipped with ten-inch diameter inlet and outlet ports to minimize pressure drop.

4.5 Treatment System Area

The treatment area will be located inside the existing site building west of MW-6. The treatment area will house the following equipment: two soil vapor extraction blowers, one air sparge blower, two vapor phase carbon adsorption units, three pipe manifold systems and all piping and electrical appurtances. The treatment area will take up an area approximately 30 ft. by 30 ft. square.

In addition to the treatment area, an enclosure for the shallow soil vapor extraction piping manifold will be located outside the building in the area of MW-1. A 8 ft. by 8 ft. concrete pad will be installed to support the piping manifold and enclosure. The enclosure will be of "dog house" type construction and will provide security and access for the piping manifold.

5.0 HEALTH AND SAFETY

In accordance with the requirements of the federal Occupational, Safety and Health Administration (OSHA) 29 CFR 1910 and 29 CFR 1929, a Site Specific Health and Safety Plan will be prepared. The plan will address the physical and chemical hazards posed to installation personnel, subcontractors and Wheeling-Pittsburgh Steel employees. The plan will include a description of air monitoring activities for gases or particulates that may be present at the site or liberated into the air as the result of site activities. A section of the plan will define the air monitoring and other procedures required while working inside the building. The plan will also include a description of contingency measures, if applicable, for containing contamination during the performance of site investigation activities.

6.0 SYSTEM START-UP AND OPERATION AND MAINTENANCE

The start-up and operation and maintenance plan developed for this site has been designed to allow collection of data necessary to ensure proper operation of the systems and to allow Wheeling-Pittsburgh Steel and BUSTR to track the progress of the remedial activities. This start up and O&M plan has been divided into four time periods:

- Baseline Monitoring: prior to start-up of the remediation system
- Start-up: the first two weeks of SVE system operation which includes the first week of air sparge system operation;
- Short-term monitoring: the month of operation following the start-up period;
- Long-term monitoring: the remainder of system operation.

6.1 Baseline Monitoring

Prior to activation of the soil vapor extraction and air sparging systems, the following parameters will be monitored to establish baseline conditions:

- The groundwater elevation will be measured at each monitoring well;
- Groundwater samples will be collected from each groundwater monitoring well;
- The pressure will be measured at each groundwater monitoring well and the monitoring points installed to conduct the pilot study;
- The dissolved oxygen concentration will be measured in a grab sample collected from each groundwater monitoring well.

6.2 Start-up Monitoring

The shallow and deep soil vapor extraction systems will be activated first. On the seventh day of operation, the air sparge system will be activated.

Soil Vapor Extraction Systems Start-Up

After the baseline parameters have been measured, the shallow soil vapor extraction system will be activated. The system will be monitored after one hour of operation and on the third, fifth and seventh day of operation. The following conditions will be monitored:

- Pressure (vacuum) in each monitoring well and the monitoring points installed to conduct the pilot study (after one hour of operation and on days 3, 5 and 7);
- System air extraction rates (after one hour of operation and on days 3, 5 and 7);
- Volatile organic compound concentrations in the system off-gas (before and after carbon treatment) using a field photoionization detector (after one hour of operation and on days 3, 5 and 7);
- Groundwater elevation in each monitoring well (on days 3, 5 and 7); and
- Dissolved oxygen concentrations in groundwater at each monitor well (day 7).

In addition, air samples will be collected from the influent and effluent sides of the air treatment system after one hour of operation and on day 7. These samples will be submitted to an environmental laboratory to be analyzed for BTEX and C_5 through C_{10} Hydrocarbons.

<u>Air Sparge System Start-Up</u>

On the seventh day of operation of the shallow and deep soil vapor extractions system, the air sparge system will be activated. The system will be monitored after one hour of operation and on the ninth, eleventh and fourteen day of operation. Days of operation are based on the initial start-up of the shallow and deep soil vapor extraction system. The following conditions will be monitored:

- Pressure (vacuum) in each monitoring well and the monitoring points installed to conduct the pilot study (after one hour of operation and on days 9, 11 and 14);
- Soil vapor extraction and air injection rates (after one hour of operation and on days 9, 11 and 14);
- Volatile organic compound concentrations in the system off-gas (before and after carbon treatment) using a field photoionization detector (after one hour of operation and on days 9, 11 and 14);
- Groundwater elevation in each monitoring well (on days 9, 11 and 14); and
- Dissolved oxygen concentrations in groundwater at each monitor well (after one hour of operation and on days 9, 11 and 14).

In addition, air samples will be collected from the influent and effluent sides of the air treatment system after one hour of operation and on day 14. These samples will be submitted to an environmental laboratory to be analyzed for BTEX and C_5 through C_{10} Hydrocarbons.

6.3 Short-Term Monitoring

For the first month after completion of System Start-Up field activities, the system will be monitored on a weekly basis (once per week) for four weeks. During each weekly visit, the following parameters will be measured:

- Pressure (vacuum) in each monitoring well and the monitoring points installed to conduct the pilot study;
- Soil vapor extraction and air injection rates;
- Volatile organic compound concentrations in the system off-gas (before and after carbon treatment) using a field photoionization detector;
- Groundwater elevation in each monitoring well; and
- Dissolved oxygen concentrations in groundwater at each monitor well.

Periodically, air samples will be collected from each of the following locations:

- Shallow soil vapor extraction system air stream (before treatment);
- Deep soil vapor extraction system air stream (before treatment);
- Combined air stream, collected from between up-stream and down stream granular activated carbon (GAC) vessels;
- After treatment by both GAC vessels.

These samples will be submitted to an environmental laboratory to be analyzed for BTEX and C_4 through C_{10} hydrocarbons. The results will be reviewed and used to:

- Ensure compliance with air discharge permit requirements;
- Evaluate system effectiveness; and
- Predict when breakthrough of the primary air treatment system will occur and allow scheduling of carbon change-out of the primary air treatment system.

6.4 Long-Term Monitoring

After completion of the one month Short-Term Monitoring Program, a Long-Term Monitoring Program will be implemented. The program will consist of bi-monthly (twice per month) site visits to monitor the system operation of the system. During each site visit, the following parameters will be measured:

- Pressure (vacuum) in each monitoring well and the monitoring points installed to conduct the pilot study;
- Soil vapor extraction and air injection rates;
- Volatile organic compound concentrations in the system off-gas (before and after carbon treatment) using a field photoionization detector;
- Groundwater elevation in each monitoring well; and
- Dissolved oxygen concentrations in groundwater at each monitor well.

Periodically, groundwater samples will be collected from monitor wells MW-6D and MW-9D. These samples will be laboratory analyzed for BTEX and TPH as Gasoline. The results will be reviewed on a monthly basis to determine when asymptotic closure criteria are met.

Periodically, air samples will be collected from each of the following locations:

- Shallow soil vapor extraction system air stream (pre-treatment);
- Deep soil vapor extraction system air stream (pre-treatment);
- Combined air stream, collected from between up-stream and down stream GAC vessels;
- After treatment by both GAC vessels.

These samples will be submitted to an environmental laboratory to be analyzed for BTEX and C_5 through C_{10} Hydrocarbons. The data will be reviewed and summarized on a monthly basis to:

- Ensure air discharge permit compliance;
- Evaluate system effectiveness;
- Predict carbon break-through; and
- Determine if asymptotic closure criteria have been met.

7.0 CLOSURE DETERMINATION

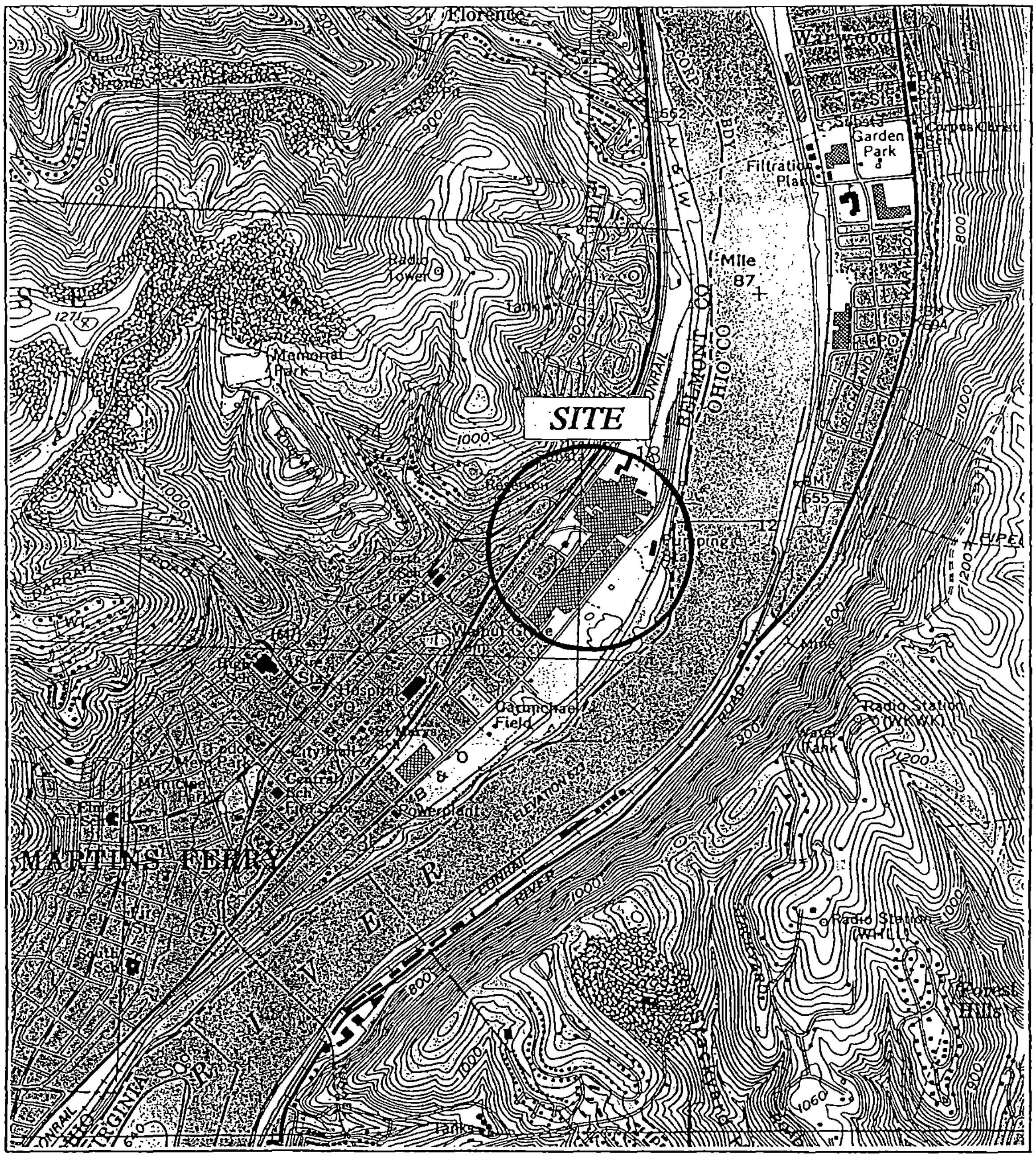
The soil vapor extraction system will be operated for a minimum of one year. After one year of operation, the results of the groundwater sampling and analysis program will be reviewed against the Category 3 action levels. If the samples results show that the groundwater concentrations are lower than the action limits a "no further action status" will be requested from BUSTR.

If the Category 3 action limits have not been achieved an alternative method will be employed to determine when to apply to BUSTR for a determination of no further action. The elements of the alternative approach are described below:

- The concentration of volatile organic compounds in the effluent from the shallow soil vapor extraction systems have declined and asymptotic[2] conditions have been achieved;
- The concentration of volatile organic compounds in the effluent from the deep soil vapor extraction systems have declined and asymptotic conditions have been achieved;
- The concentration of dissolved benzene in groundwater samples collected from MW-6D has declined and asymptotic conditions have been achieved; and
- The concentration of dissolved benzene in groundwater samples collected from MW-9D has declined and asymptotic conditions have been achieved.

[2]Asymptotic conditions will be satisfied if the asymptote criterion described in Method 1 in API publication 4510 are satisfied over a consecutive 6 month period.

FIGURES



0 2000

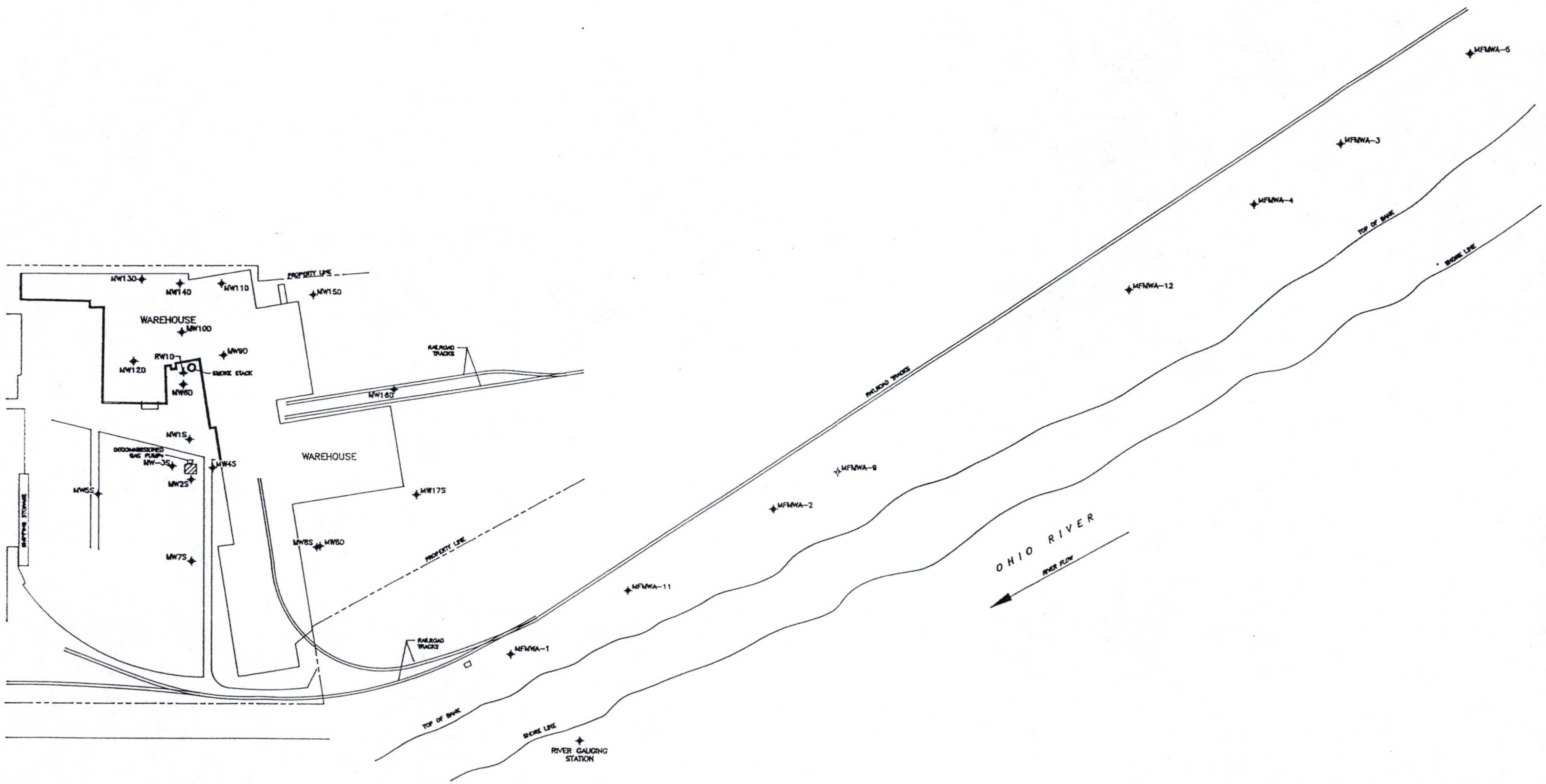
SCALE FEET

N

SOURCE: U.S.G.S. TOPOGRAPHIC QUADRANGLE MAP; WHEELING, WVA-OHIO; 1968. 7.5 MINUTE SERIES.

FIGURE 1
SITE LOCATION MAP
WHEELING PITTSBURGH STEEL CORPORATION
MARINS FERRY PLANT No. 1
MARTINS FERRY, OHIO

GROUNDWATER TECHNOLOGY



LEGEND

- MONITORING WELL
- RECOVERY WELL
- • GASOLINE TANK AND PUMP EXCAVATED AND REMOVED
- S SHALLOW WELL
- D DEEP WELL
- MFMWA MARTINS FERRY MUNICIPAL WATER AUTHORITY
- APPROXIMATE LOCATION OF FORMER UNDERGROUND STORAGE TANK

N

100 0 100 200
SCALE FEET

SOURCE: WHEELING PITTSBURGH STEEL CORPORATION; and PENN LAND SURVEYORS: WORKSHEET #1 – "WORKSHEET SHOWING ENTIRE AREA" MARCH 17, 1995, and WORKSHEET #2 – MAP SHOWING MONITORING WELLS IN RELATIONSHIP TO EXISTING BUILDING MARCH 17, 1995.

SIGNATURE	DATE
REVIEW HYDRO/GEO:	
PROJECT HYDRO/GEO:	
PROJECT MGR:	
CLIENT:	

GROUNDWATER TECHNOLOGY

202 COMMERCE PARK DRIVE
CRANBERRY TWP., PA 16066 (412) 776-4700

AREA SITE MAP

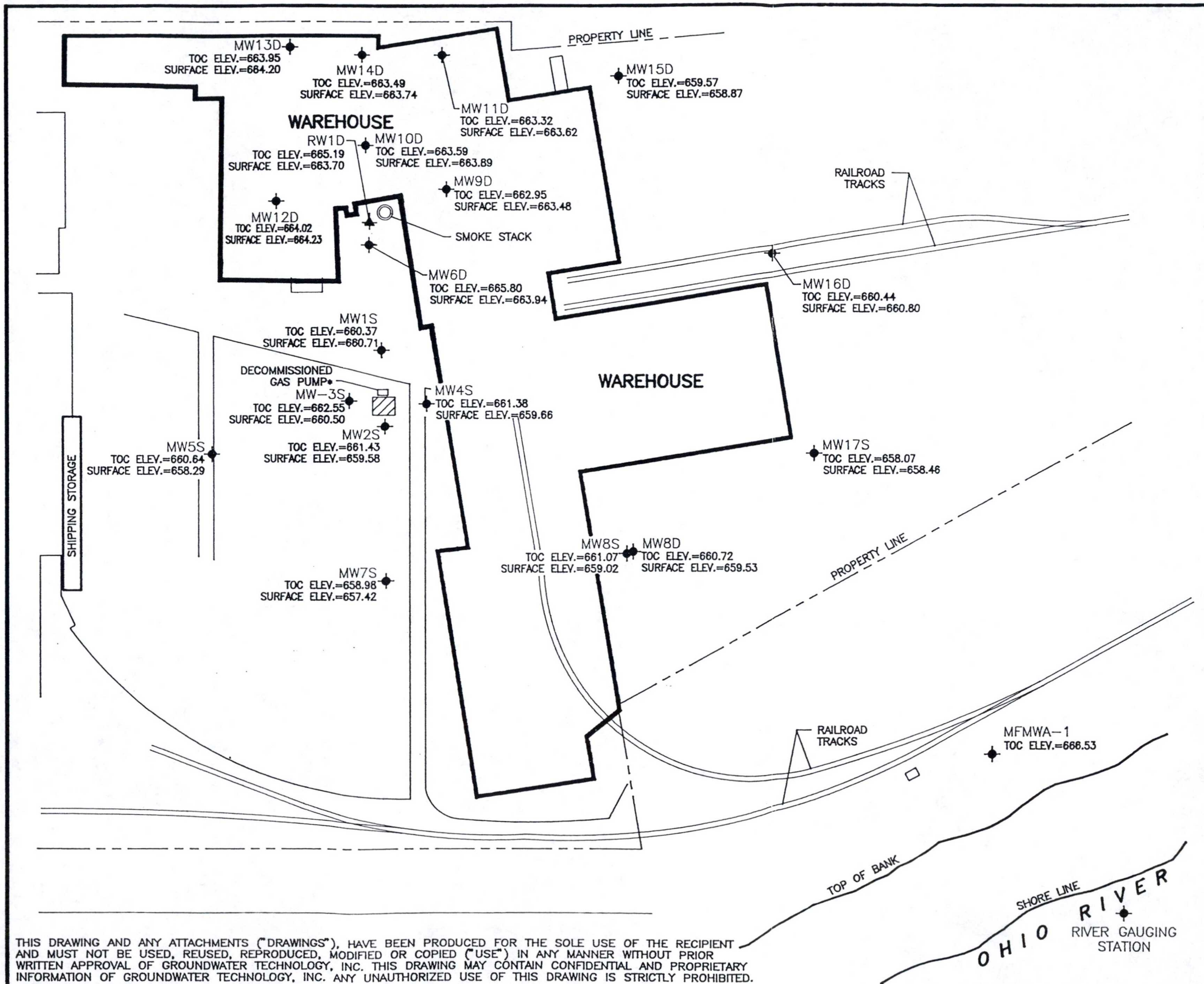
CLIENT: WHEELING PITTSBURGH STEEL CORPORATION

LOCATION: MARTINS FERRY PLANT NO. 1

DESIGNED BY:	DETAILED BY:	CHECKED BY:
SEE SOURCE	KRE	

DRAWING DATE:	ACAD FILE:
3/29/95	0076SITB
PROJECT NO.:	NOTES:
04100-0076	

FIGURE 2



LEGEND

◆	MONITORING WELL
▲	RECOVERY WELL
*	GASOLINE TANK AND PUMP EXCAVATED AND REMOVED
S	SHALLOW WELL
D	DEEP WELL
MFMWA	MARTINS FERRY MUNICIPAL WATER AUTHORITY
TOC	TOP OF CASING
▨	APPROXIMATE LOCATION OF FORMER UNDERGROUND STORAGE TANK

NOTE: ALL ELEVATIONS ARE IN FEET.

N

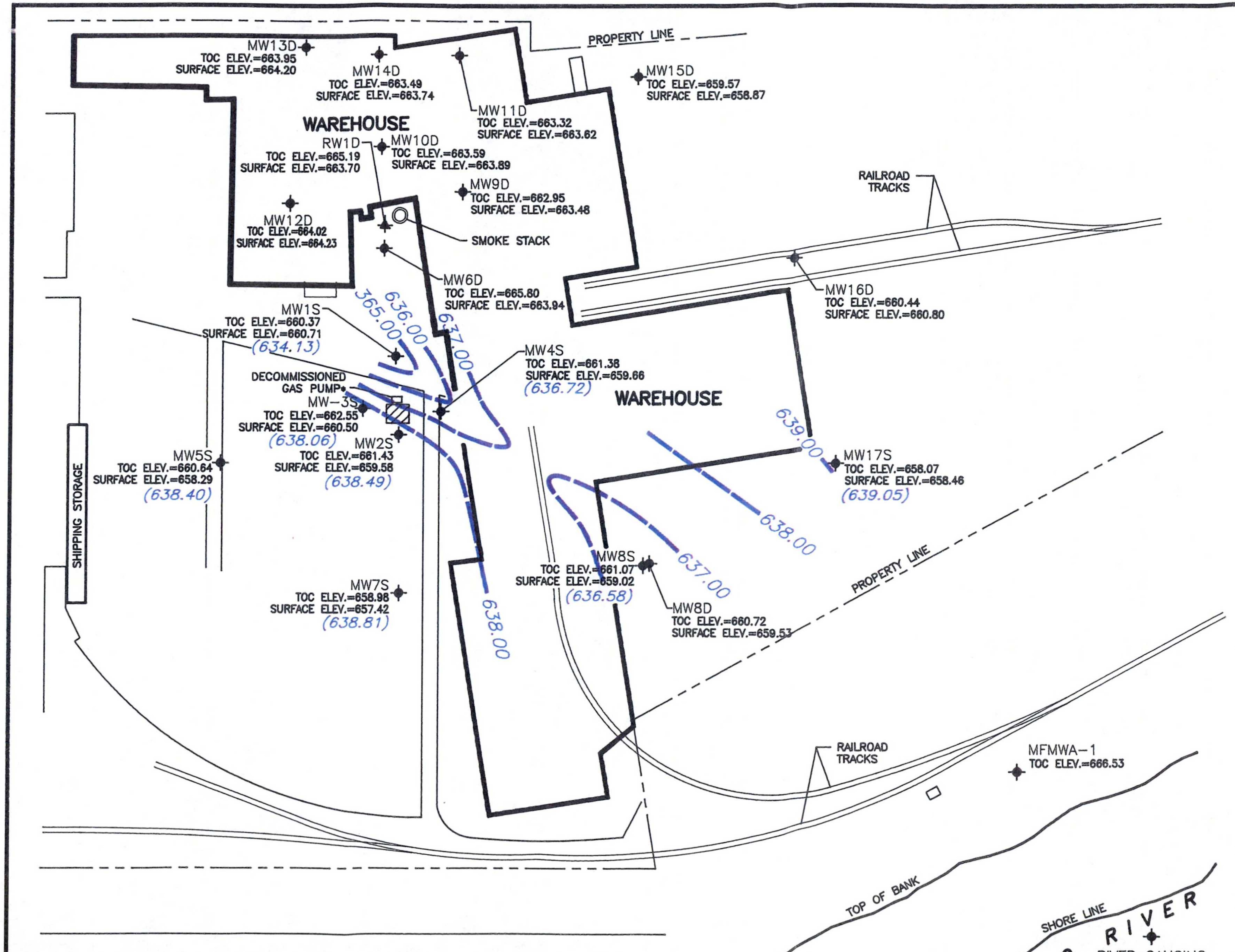
0 100 200

SCALE FEET

SOURCE: WHEELING PITTSBURGH STEEL CORPORATION; and PENN LAND SURVEYORS: WORKSHEET #1 – "WORKSHEET SHOWING ENTIRE AREA" MARCH 17, 1995, and WORKSHEET #2 – MAP SHOWING MONITORING WELLS IN RELATIONSHIP TO EXISTING BUILDING MARCH 17, 1995.

GROUNDWATER TECHNOLOGY
202 COMMERCE PARK DRIVE
CRANBERRY TWP., PA 16066
(412) 776-4700

REV. NO.:	DRAWING DATE: 3/29/95	ACAD FILE: 0076SITE	
SITE MAP			
CLIENT: WHEELING PITTSBURGH STEEL CORPORATION			PM:
LOCATION: MARTINS FERRY PLANT NO. 1			PE/RG:
DESIGNED: SEE SOURCE	DETAILED: KRE	PROJECT NO.: 04100-0076	FIGURE: 3



LEGEND

✦	MONITORING WELL
✦	RECOVERY WELL
*	GASOLINE TANK AND PUMP EXCAVATED AND REMOVED
S	SHALLOW WELL
D	DEEP WELL
MFMWA	MARTINS FERRY MUNICIPAL WATER AUTHORITY
TOC	TOP OF CASING
▨	APPROXIMATE LOCATION OF FORMER UNDERGROUND STORAGE TANK
(643.13)	RELATIVE WATER LEVEL ELEVATION IN FEET
— —	INFERRED GROUNDWATER ELEVATION CONTOUR IN FEET CONTOUR INTERVAL = 1.00 FEET

NOTE: ALL ELEVATIONS ARE IN FEET.

N

0 100 200

SCALE FEET

SOURCE: WHEELING PITTSBURGH STEEL CORPORATION; and PENN LAND SURVEYORS: WORKSHEET #1 – "WORKSHEET SHOWING ENTIRE AREA" MARCH 17, 1995, and WORKSHEET #2 – MAP SHOWING MONITORING WELLS IN RELATIONSHIP TO EXISTING BUILDING MARCH 17, 1995.

MFMWA-11
TOC ELEV.=651.20

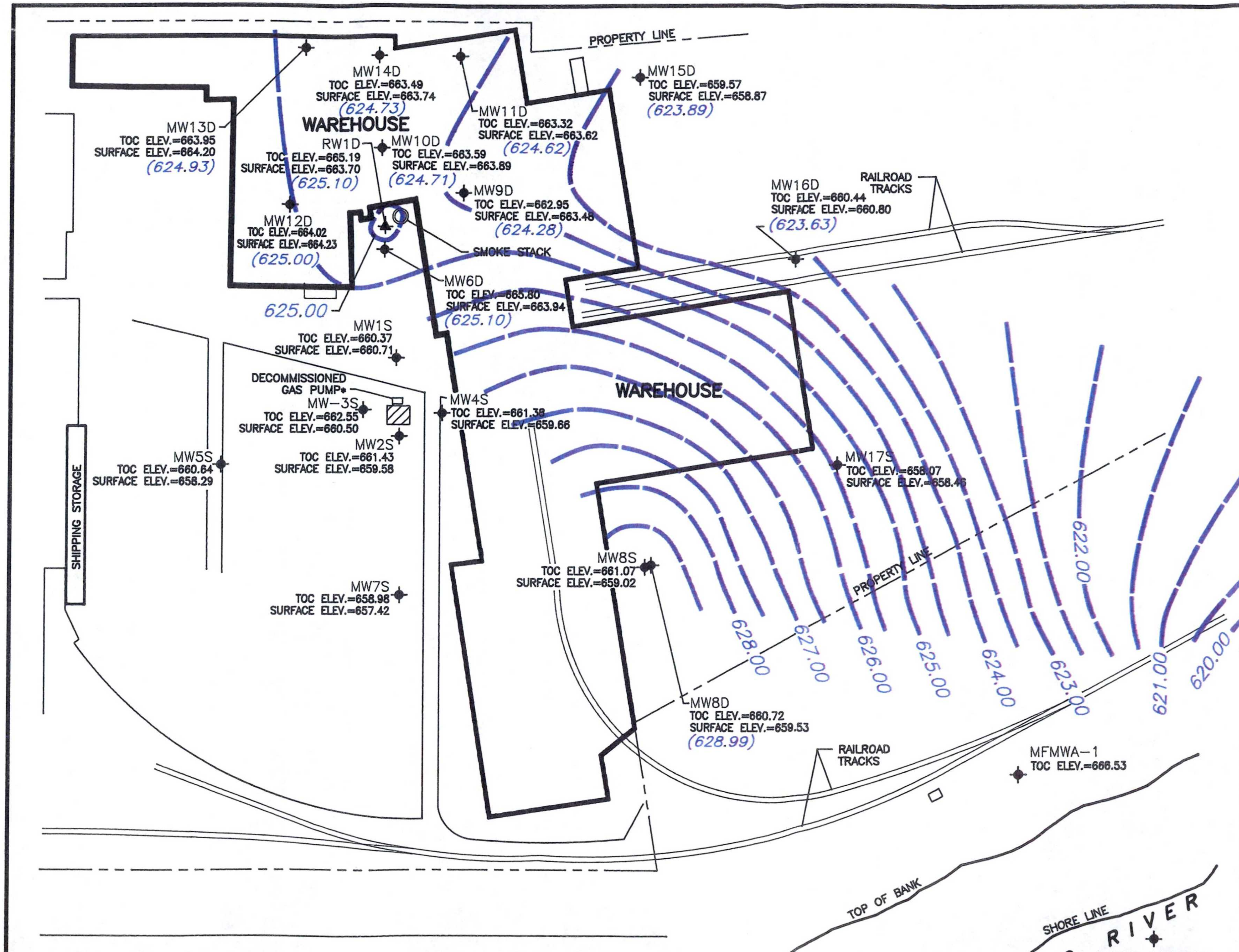
GROUNDWATER TECHNOLOGY
202 COMMERCE PARK DRIVE
CRANBERRY TWP., PA 16066
(412) 776-4700

REV. NO.:	DRAWING DATE: 3/29/95	ACAD FILE: 0076GUM5

GROUNDWATER ELEVATION CONTOURS UPPER SATURATED ZONE 14 MARCH 1995

CLIENT: WHEELING PITTSBURGH STEEL CORPORATION	PM:
LOCATION: MARTINS FERRY PLANT NO. 1	PE/RG:

DESIGNED:	DETAILED:	PROJECT NO.:	FIGURE:
BS	KRE	04100-0076	4



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LEGEND

Symbol	Description
✦	MONITORING WELL
✦	RECOVERY WELL
*	GASOLINE TANK AND PUMP EXCAVATED AND REMOVED
S	SHALLOW WELL
D	DEEP WELL
MFMWA	MARTINS FERRY MUNICIPAL WATER AUTHORITY
TOC	TOP OF CASING
▨	APPROXIMATE LOCATION OF FORMER UNDERGROUND STORAGE TANK
(624.93)	RELATIVE WATER LEVEL ELEVATION IN FEET
— —	INFERRED GROUNDWATER ELEVATION CONTOUR IN FEET CONTOUR INTERVAL = 0.50 FEET

N

0 100 200
SCALE FEET

SOURCE: WHEELING PITTSBURGH STEEL CORPORATION; and PENN LAND SURVEYORS: WORKSHEET #1 – "WORKSHEET SHOWING ENTIRE AREA" MARCH 17, 1995, and WORKSHEET #2 – MAP SHOWING MONITORING WELLS IN RELATIONSHIP TO EXISTING BUILDING MARCH 17, 1995.

GROUNDWATER TECHNOLOGY
202 COMMERCE PARK DRIVE
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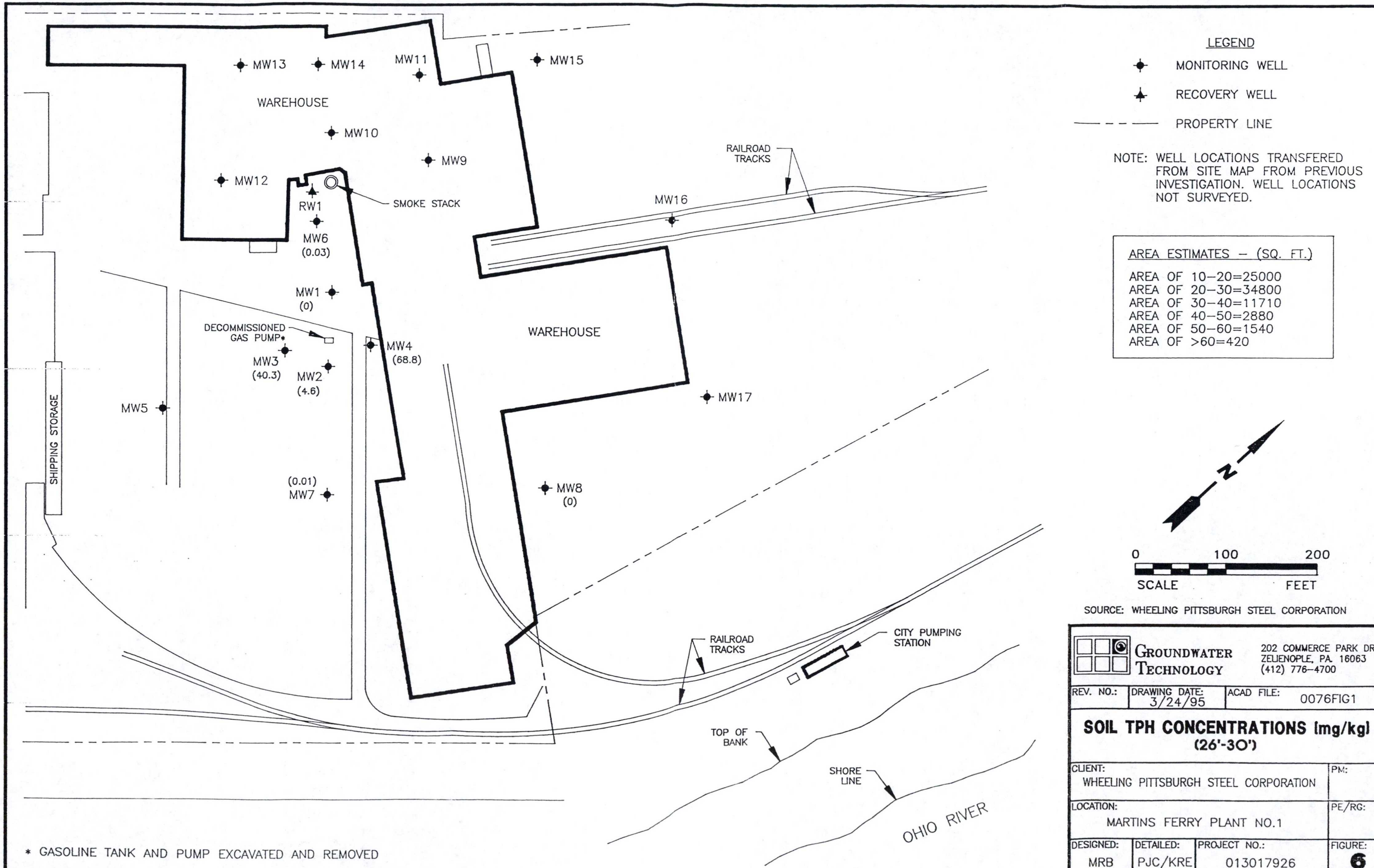
(412) 776-4700

REV. NO.:	DRAWING DATE: 3/29/95	ACAD FILE: 0076GLM5

GROUNDWATER ELEVATION CONTOURS LOWER SATURATED ZONE 14 MARCH 1995

CLIENT: WHEELING PITTSBURGH STEEL CORPORATION	PM:
LOCATION: MARTINS FERRY PLANT NO. 1	PE/RG:

DESIGNED:	DETAILED:	PROJECT NO.:	FIGURE:
BS	KRE	04100-0076	5



GROUNDWATER TECHNOLOGY
202 COMMERCE PARK DR.
ZELIENOPLE, PA 16063
(412) 776-4700

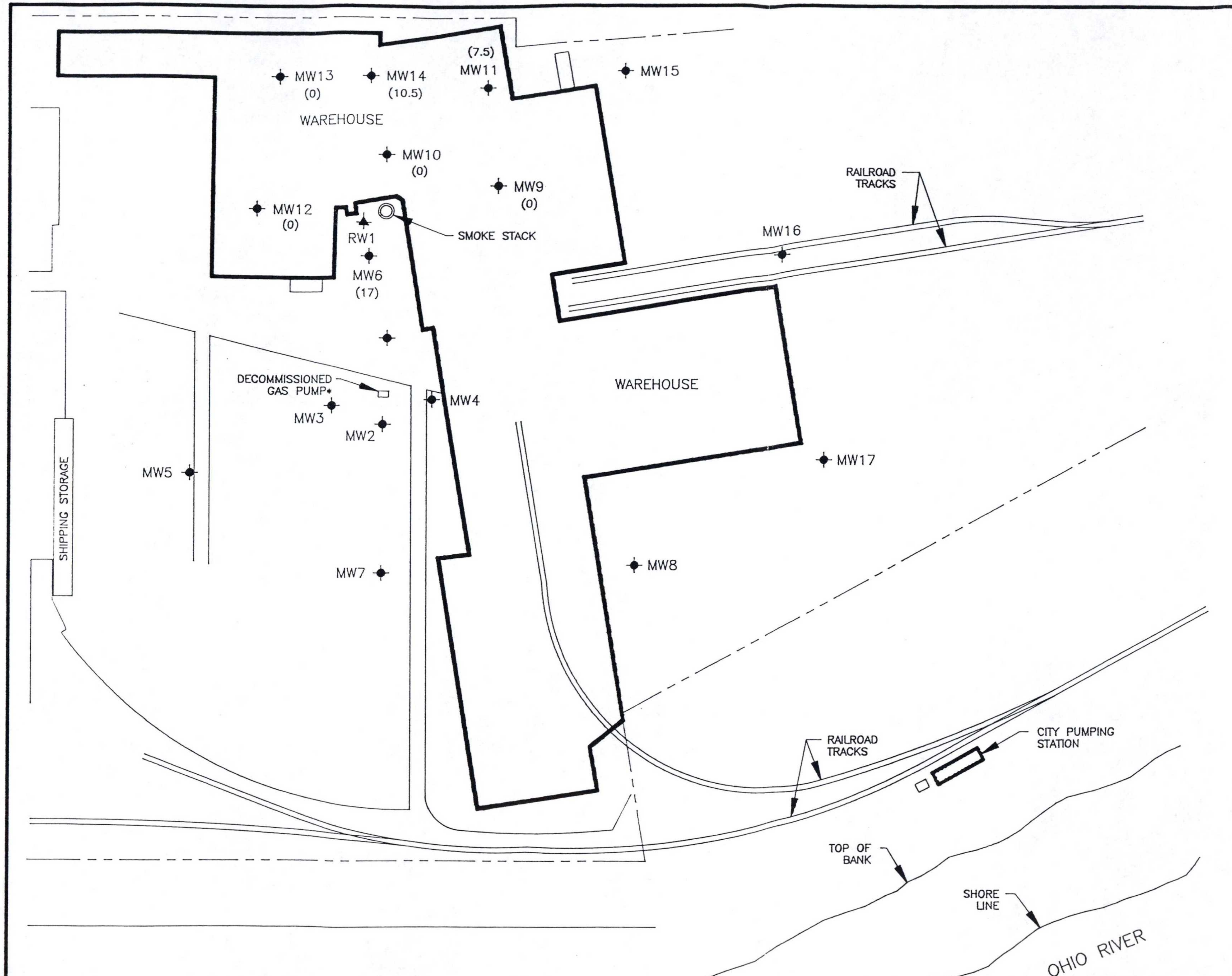
REV. NO.:	DRAWING DATE: 3/24/95	ACAD FILE: 0076FIG1

SOIL TPH CONCENTRATIONS (mg/kg)
(26'-30')

CLIENT: WHEELING PITTSBURGH STEEL CORPORATION
PM:

LOCATION: MARTINS FERRY PLANT NO.1
PE/RG:

DESIGNED:	DETAILED:	PROJECT NO.:	FIGURE:
MRB	PJC/KRE	013017926	6



* GASOLINE TANK AND PUMP EXCAVATED AND REMOVED

LEGEND

- MONITORING WELL
- RECOVERY WELL
- PROPERTY LINE

NOTE: WELL LOCATIONS TRANSFERED FROM SITE MAP FROM PREVIOUS INVESTIGATION. WELL LOCATIONS NOT SURVEYED.

AREA ESTIMATES – (SQ. FT.)

AREA OF 5=43860
AREA OF 5–10=65400
AREA OF 10–15=8550
AREA OF >15=1290

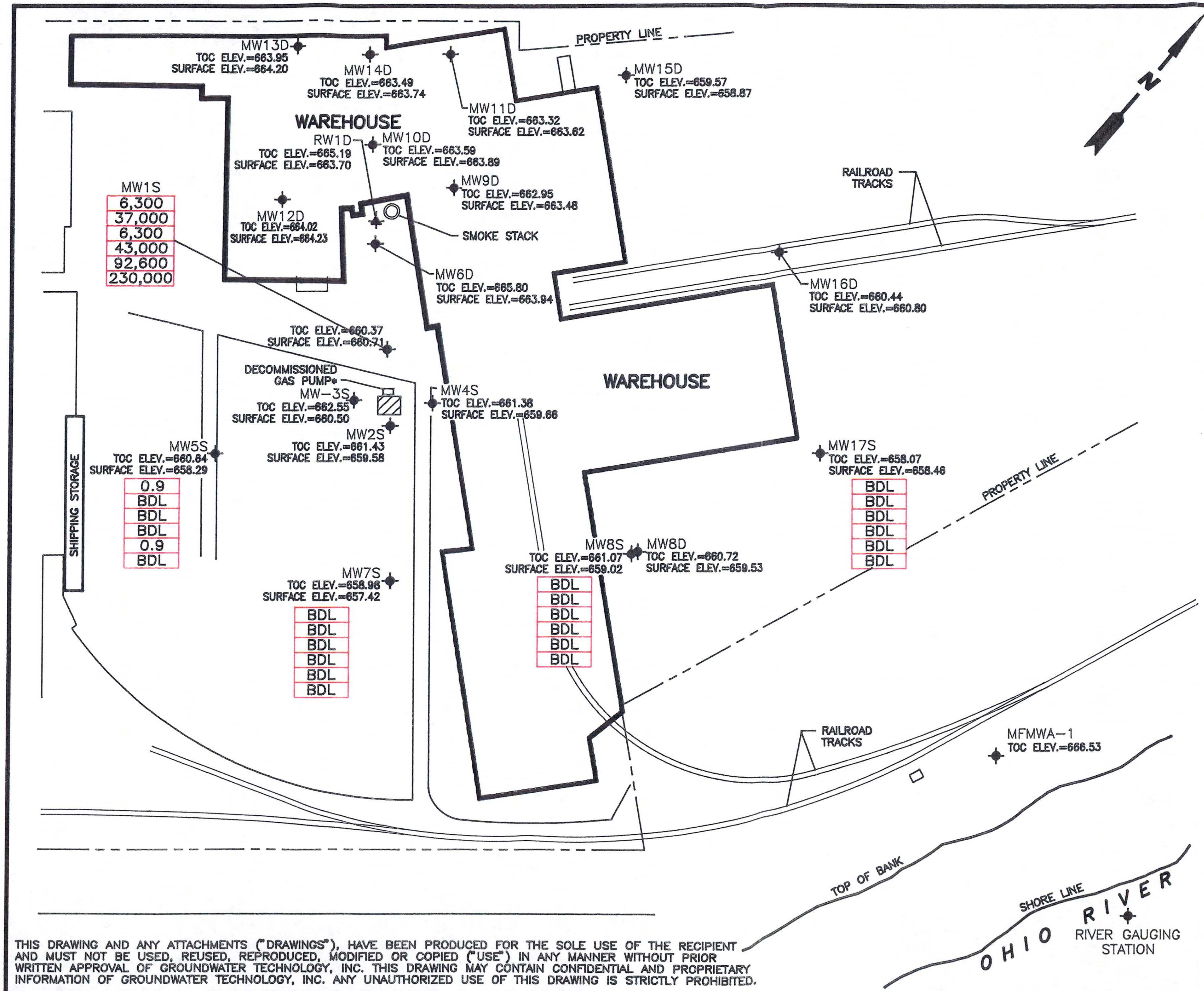
SOURCE: WHEELING PITTSBURGH STEEL CORPORATION

GROUNDWATER TECHNOLOGY
202 COMMERCE PARK DR.
ZELIENOPLE, PA. 16063
(412) 776–4700

REV. NO.:	DRAWING DATE: 3/24/95	ACAD FILE: 0076FIG2

SOIL TPH CONCENTRATIONS (mg/kg) (34'-38')

CLIENT: WHEELING PITTSBURGH STEEL CORPORATION			PM:
LOCATION: MARTINS FERRY PLANT NO.1			PE/RG:
DESIGNED: MRB	DETAILED: PJC/KRE	PROJECT NO.: 013017926	FIGURE: 7



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LEGEND

Symbol	Description
⌖	MONITORING WELL
⌖	RECOVERY WELL
*	GASOLINE TANK AND PUMP EXCAVATED AND REMOVED
S	SHALLOW WELL
D	DEEP WELL
MFMWA	MARTINS FERRY MUNICIPAL WATER AUTHORITY
TOC	TOP OF CASING
▨	APPROXIMATE LOCATION OF FORMER UNDERGROUND STORAGE TANK
6,300	BENZENE CONCENTRATION (ug/L)
37,000	TOLUENE CONCENTRATION (ug/L)
6,300	ETHYLBENZENE CONCENTRATION (ug/L)
43,000	XYLENES CONCENTRATION (ug/L)
92,600	TOTAL BTEX CONCENTRATION (ug/L)
230,000	TPH AS GASOLINE CONCENTRATION (ug/L)
BTEX	BENZENE, TOLUENE, ETHYLBENZENE AND XYLENES
TPH	TOTAL PETROLEUM HYDROCARBONS
BDL	BELOW DETECTION LIMITS
(ug/L)	MICROGRAMS PER LITER

NOTE: ALL ELEVATIONS ARE IN FEET.

SCALE 0 100 200 FEET

SOURCE: WHEELING PITTSBURGH STEEL CORPORATION; and PENN LAND SURVEYORS: WORKSHEET #1 – "WORKSHEET SHOWING ENTIRE AREA" MARCH 17, 1995, and WORKSHEET #2 – MAP SHOWING MONITORING WELLS IN RELATIONSHIP TO EXISTING BUILDING MARCH 17, 1995.

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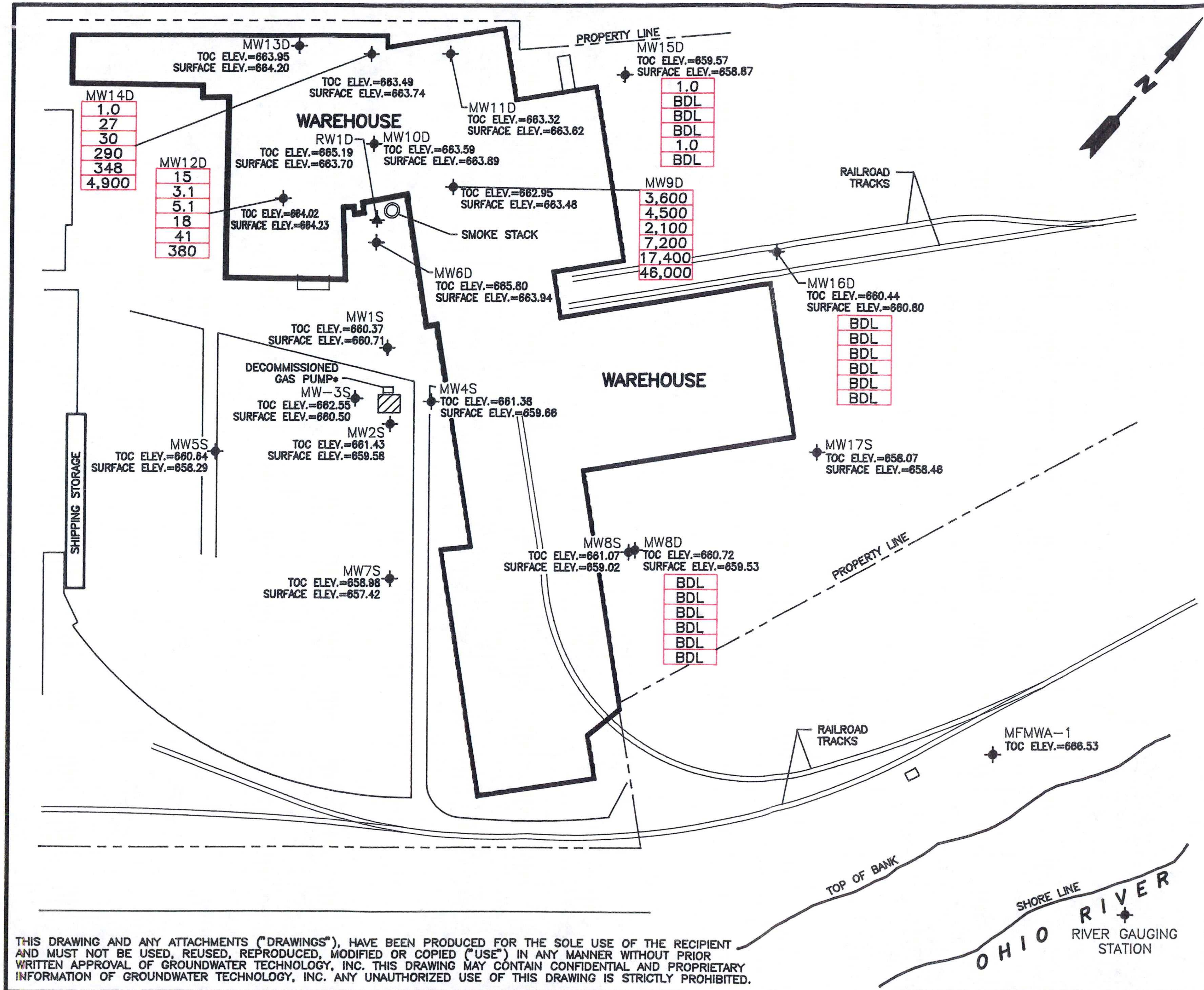
(412) 776-4700

REV. NO.:	DRAWING DATE: 3/30/95	ACAD FILE: 0076AUD4	

DISTRIBUTION OF DISSOLVED BTEX and TPH UPPER SATURATED ZONE 20 DECEMBER 1994

CLIENT: WHEELING PITTSBURGH STEEL CORPORATION	PM:
LOCATION: MARTINS FERRY PLANT NO. 1	PE/RG:

DESIGNED:	DETAILED:	PROJECT NO.:	FIGURE:
BS	KRE	04100-0076	8



LEGEND

✦	MONITORING WELL
✦	RECOVERY WELL
*	GASOLINE TANK AND PUMP EXCAVATED AND REMOVED
S	SHALLOW WELL
D	DEEP WELL
MFMWA	MARTINS FERRY MUNICIPAL WATER AUTHORITY
TOC	TOP OF CASING
▨	APPROXIMATE LOCATION OF FORMER UNDERGROUND STORAGE TANK
3,600	BENZENE CONCENTRATION (ug/L)
4,500	TOLUENE CONCENTRATION (ug/L)
2,100	ETHYLBENZENE CONCENTRATION (ug/L)
7,200	XYLENES CONCENTRATION (ug/L)
17,400	TOTAL BTEX CONCENTRATION (ug/L)
46,000	TPH AS GASOLINE CONCENTRATION (ug/L)
BTEX	BENZENE, TOLUENE, ETHYLBENZENE AND XYLENES
TPH	TOTAL PETROLEUM HYDROCARBONS
BDL	BELOW DETECTION LIMITS
(ug/L)	MICROGRAMS PER LITER

NOTE: ALL ELEVATIONS ARE IN FEET.

0 100 200
SCALE FEET

SOURCE: WHEELING PITTSBURGH STEEL CORPORATION; and PENN LAND SURVEYORS: WORKSHEET #1 – "WORKSHEET SHOWING ENTIRE AREA" MARCH 17, 1995, and WORKSHEET #2 – MAP SHOWING MONITORING WELLS IN RELATIONSHIP TO EXISTING BUILDING MARCH 17, 1995.

GROUNDWATER TECHNOLOGY
202 COMMERCE PARK DRIVE
CRANBERRY TWP., PA 16066
(412) 776-4700

REV. NO.:	DRAWING DATE: 3/30/95	ACAD FILE: 0076ALD4

DISTRIBUTION OF DISSOLVED BTEX AND TPH LOWER SATURATED ZONE 20 DECEMBER 1994

CLIENT: WHEELING PITTSBURGH STEEL CORPORATION			PM:
LOCATION: MARTINS FERRY PLANT NO. 1			PE/RG:
DESIGNED: BS	DETAILED: KRE	PROJECT NO.: 04100-0076	FIGURE: 9

SYSTEM DESIGN DRAWINGS

SOIL VAPOR EXTRACTION AND AIR SPARGING SYSTEM

PREPARED FOR:

WHEELING PITTSBURGH STEEL CORPORATION

MARTINS FERRY, OHIO

PLANT NO.1

PROJECT NO. 04100-0076

REVISION 1

MARCH, 1995

SHEET INDEX

DWG. NO.	TITLE
Y1-1	SITE PLAN
Y2-1	AIR SPARGE POINT DETAILS AND AIR SPARGE PIPING
Y3-1	SOIL VAPOR EXTRACTION WELL DETAILS AND SOIL VAPOR EXTRACTION PIPING (DEEP WELLS)
Y4-1	SOIL VAPOR EXTRACTION WELL DETAILS AND SOIL VAPOR EXTRACTION PIPING (SHALLOW WELLS)
Y5-1	SYSTEM PIPING TRENCH CROSS-SECTIONS
Y6-1	CONSTRUCTION DETAILS
M1-1	TREATMENT EQUIPMENT LAYOUT
P1	PIPING AND INSTRUMENTATION DIAGRAM LEGEND
P2-1	PIPING AND INSTRUMENTATION DIAGRAM
E1	ELECTRICAL LEGEND
E2	ELECTRICAL ONE-LINE DIAGRAM
E3-1	HAZARDOUS AREA CLASSIFICATION DIAGRAM

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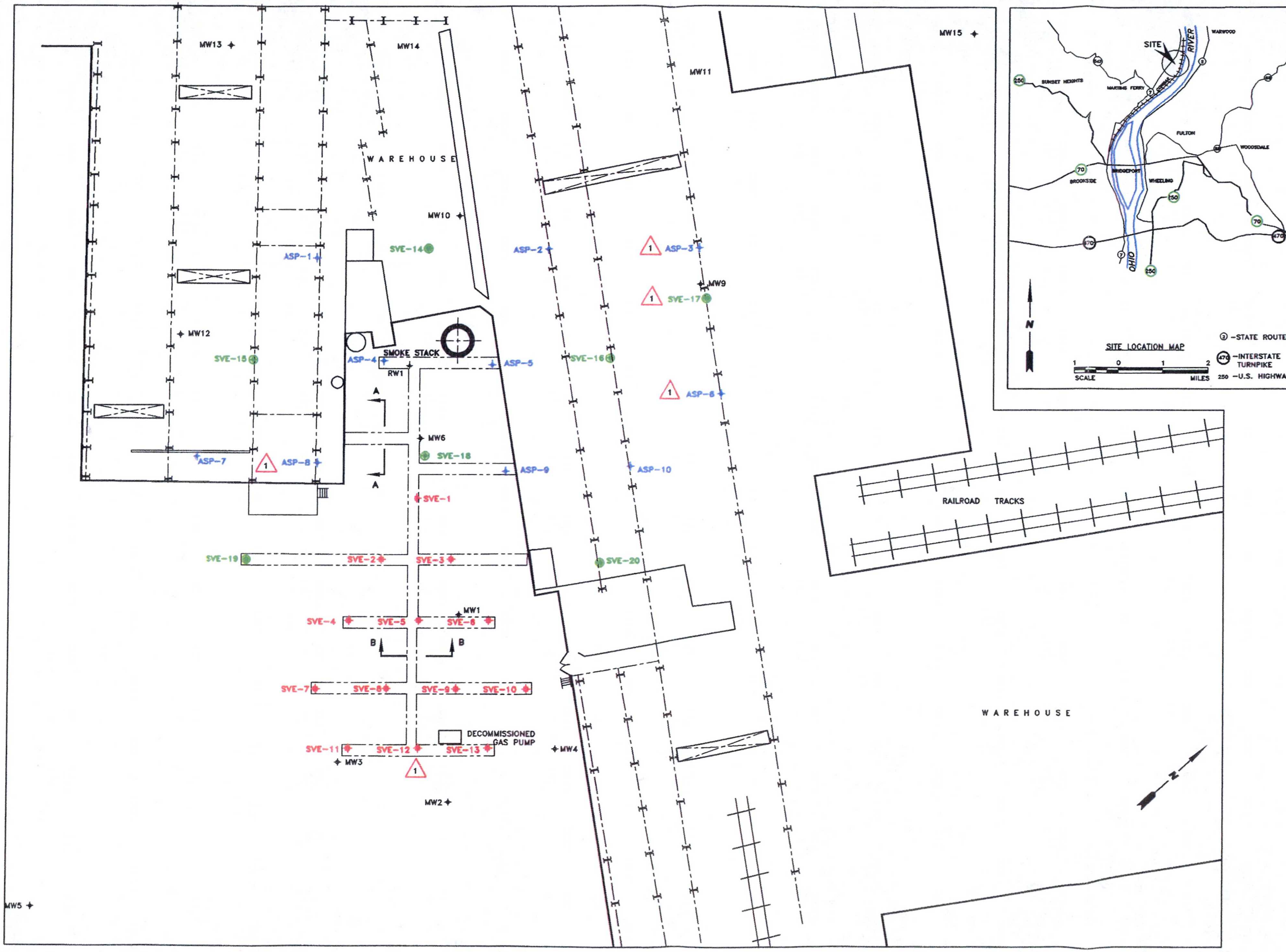
GROUNDWATER TECHNOLOGY

ACAD FILE: 0076COV1.DWG



NO.	DATE	BY	REVISION
1	3/10/95	TES	REGULATORY REVIEW AND COLLECTION OF ADDITIONAL SITE DATA

LEGEND

- MONITORING WELL
- RECOVERY WELL
- AIR SPARGE POINT
  EX.: ASP-9 – POINT IDENTIFICATION.
- SOIL VAPOR EXTRACTION WELL (DEEP)
  EX.: SVE-18 – WELL IDENTIFICATION.
- SOIL VAPOR EXTRACTION WELL (SHALLOW)
  EX.: SVE-1 – WELL IDENTIFICATION.
- SYSTEM PIPING TRENCH

NOTE:

1. MONITORING WELL LOCATIONS TRANSFERRED FROM PREVIOUS INVESTIGATION SITE MAP WELL LOCATIONS NOT SURVEYED.
2. FOR TRENCH CROSS-SECTIONS A-A & B-B SEE DWG. Y5-1

SOURCE:
WHEELING PITTSBURGH STEEL CORPORATION

20 0 20 40
SCALE FEET

SIGNATURE	DATE
REVIEW ENGR:	
PROJECT ENGR:	
PROJECT MGR:	
CLIENT:	

GROUNDWATER TECHNOLOGY
100 RIVER RIDGE DRIVE
NORWOOD, MA 02062 (617) 769-7600

WHEELING PITTSBURGH STEEL CORPORATION

MARTINS FERRY, OHIO
PLANT No.1

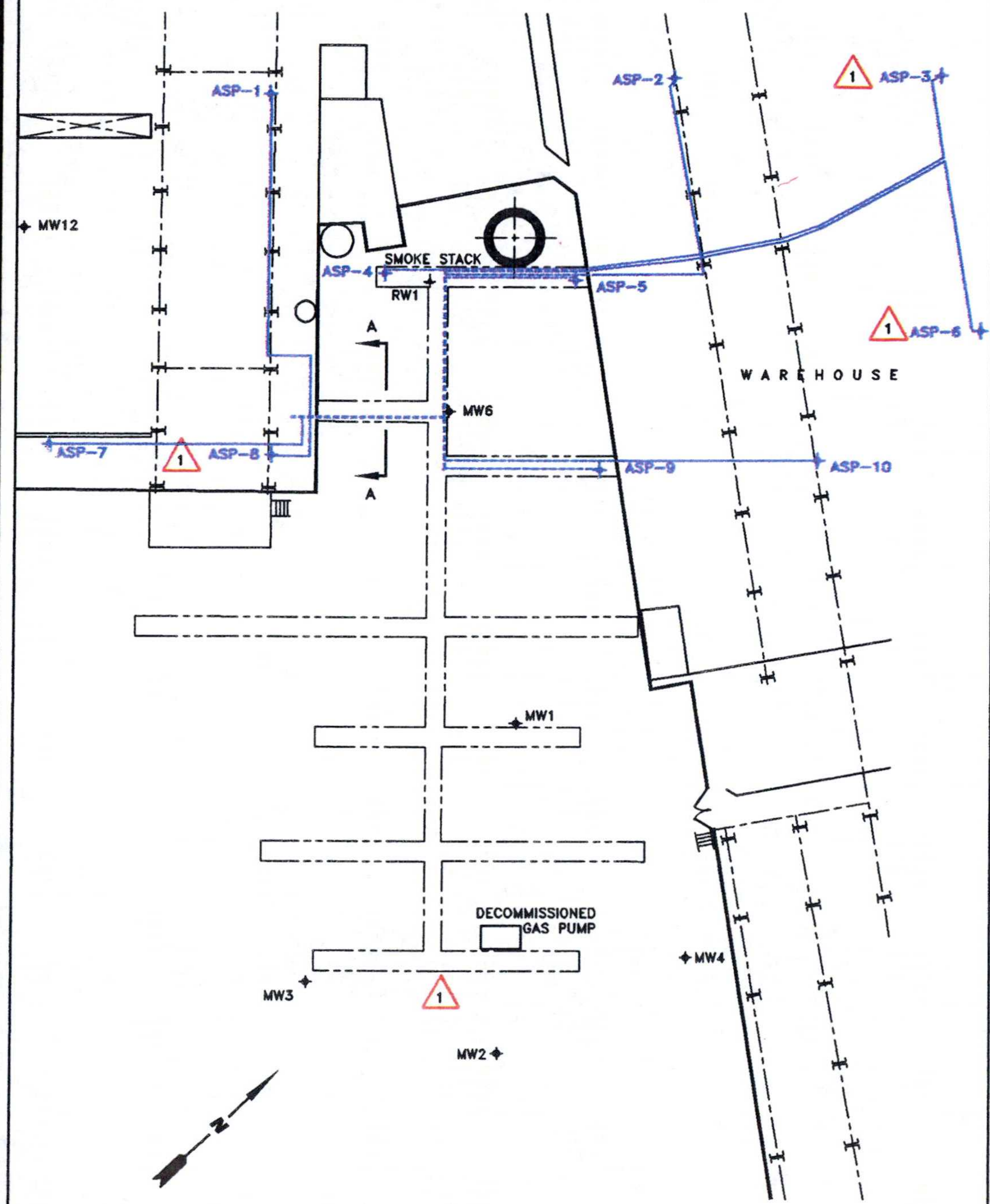
SOIL VAPOR EXTRACTION AND AIR SPARGING SYSTEM

SITE MAP

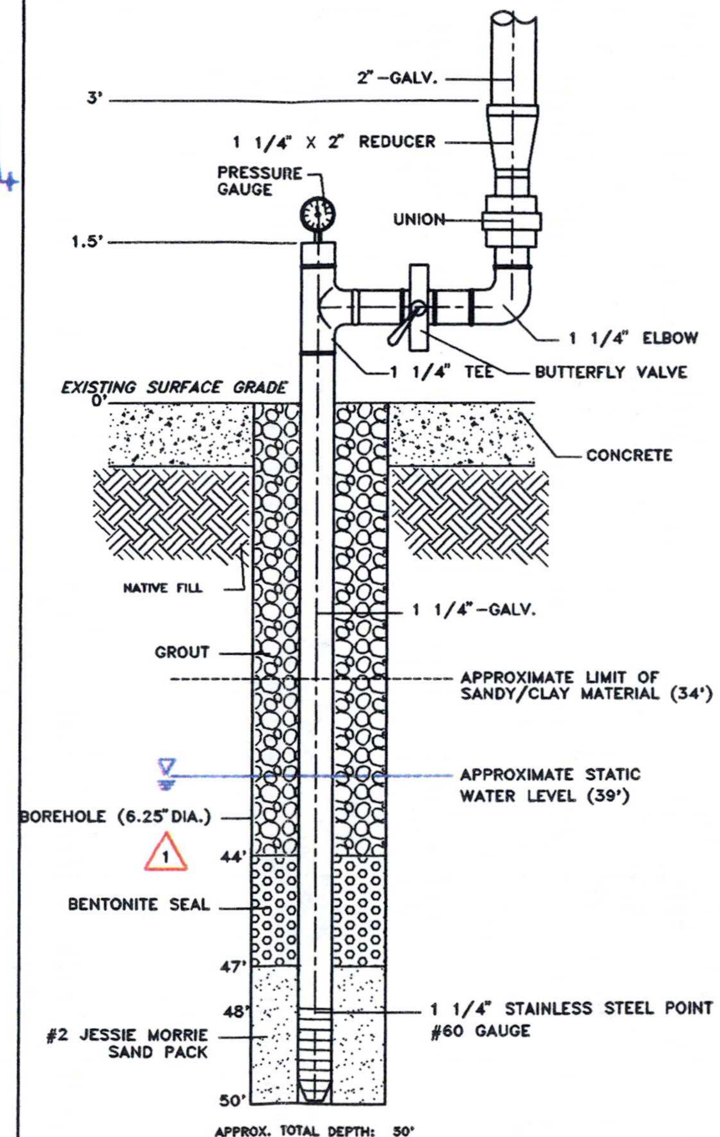
DESIGNED BY:	DETAILED BY:	CHECKED BY:
JAC/TES	VK	TES

DRAWING DATE:	FILE:
3/15/95	0076SITF
PROJECT NO.:	CONTRACT:
04100-0076	
DRAWING:	REVISION:
Y1	1

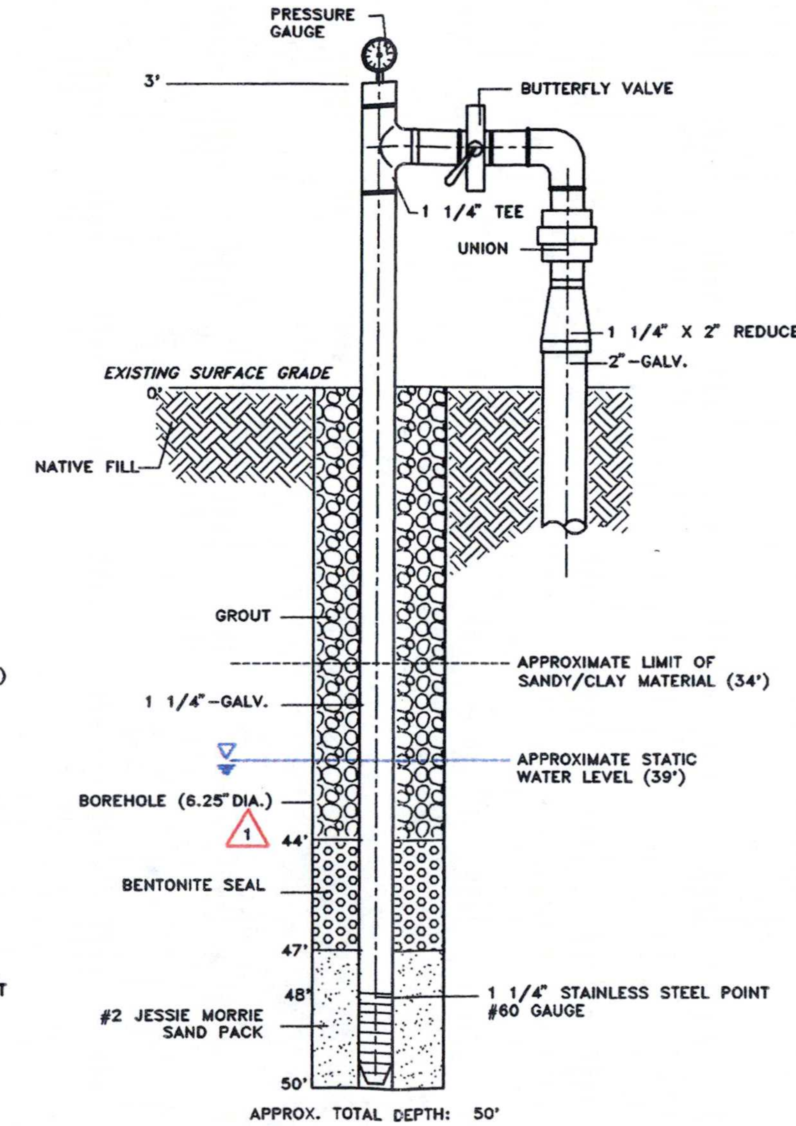
NO.	DATE	BY	REVISION
1	3/10/95	TES	REGULATORY REVIEW ~~AND COLLECTION OF~~ ADDITIONAL SITE DATA



SITE LAYOUT
AIR SPARGE SYSTEM



PROPOSED AIR SPARGE POINT
INTERIOR (TYP. OF 7)
(ASP-1,2,3,6,7,8,10)
SCALE: NOT TO SCALE



PROPOSED AIR SPARGE POINT
EXTERIOR (TYP. OF 3)
(ASP-4,5,9)
SCALE: NOT TO SCALE

NOTES:
1. SEAL PIPING PENETRATIONS WITH NON-SHRINK GROUT.
2. NUMBERS TO THE LEFT OF THE WELL DETAILS INDICATE APPROXIMATE DEPTH OF THE VARIOUS MATERIALS FOR WELL CONSTRUCTION BELOW GRADE.

LEGEND

- MONITORING WELL
- RECOVERY WELL
- AIR SPARGE POINT EX.: ASP-9 – POINT IDENTIFICATION.
- AIR SPARGE UNDERGROUND PIPING
- 2" DIA. AIR SPARGE UNDERGROUND PIPING
- 2" DIA. AIR SPARGE ABOVEGROUND PIPING
- SYSTEM PIPING TRENCH

NOTE:
1. MONITORING WELL LOCATIONS TRANSFERRED FROM PREVIOUS INVESTIGATION SITE MAP. WELL LOCATIONS NOT SURVEYED.
2. FOR TRENCH CROSS-SECTION A-A SEE DWG. Y5-1

SOURCE:
WHEELING PITTSBURGH STEEL CORPORATION

SCALE: 20 0 20 40 FEET

SIGNATURE	DATE
REVIEW ENGR:	
PROJECT ENGR:	
PROJECT MGR:	
CLIENT:	

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WHEELING PITTSBURGH STEEL CORPORATION

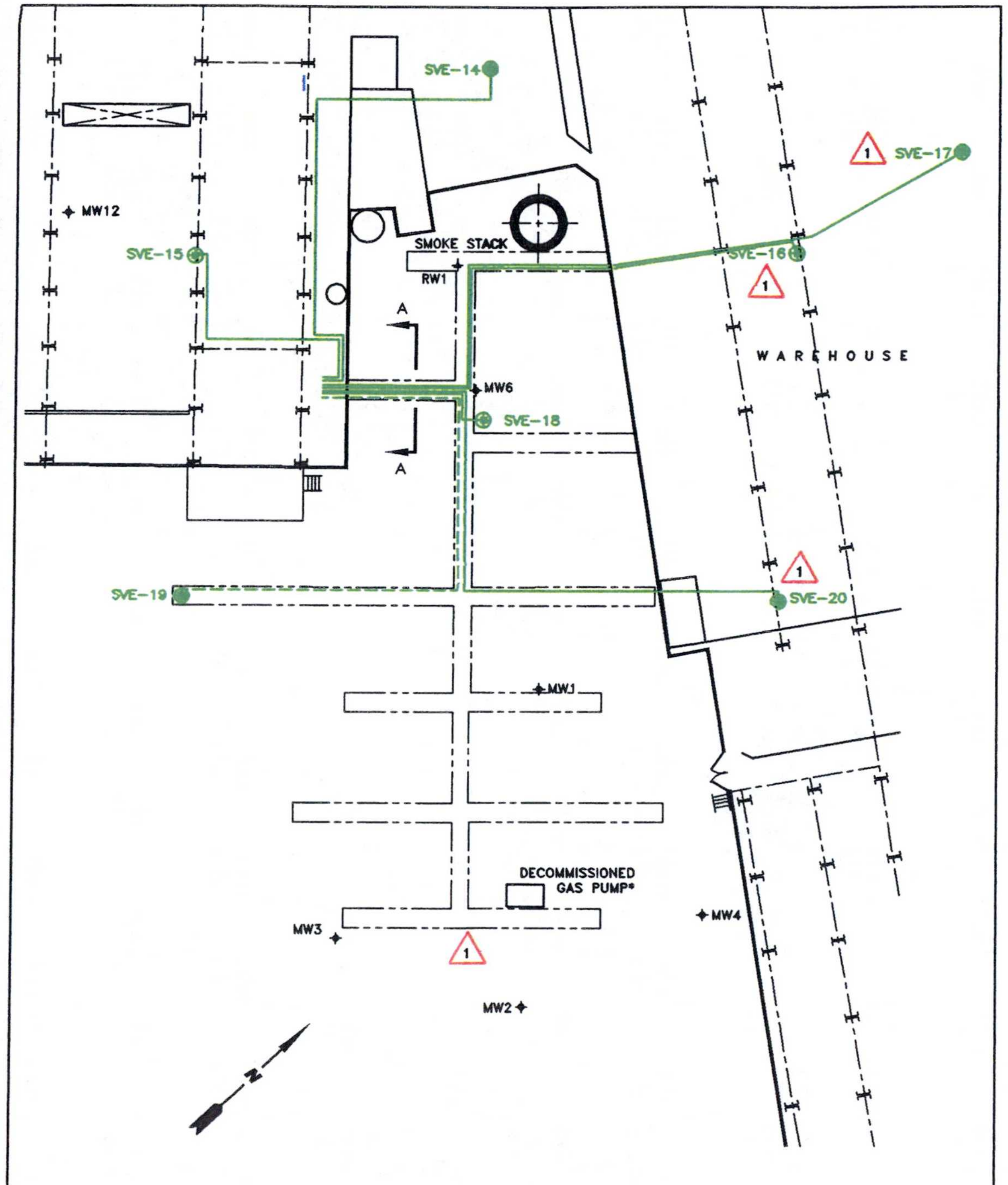
MARTINS FERRY, OHIO
PLANT No.1

SOIL VAPOR EXTRACTION AND AIR SPARGING SYSTEM

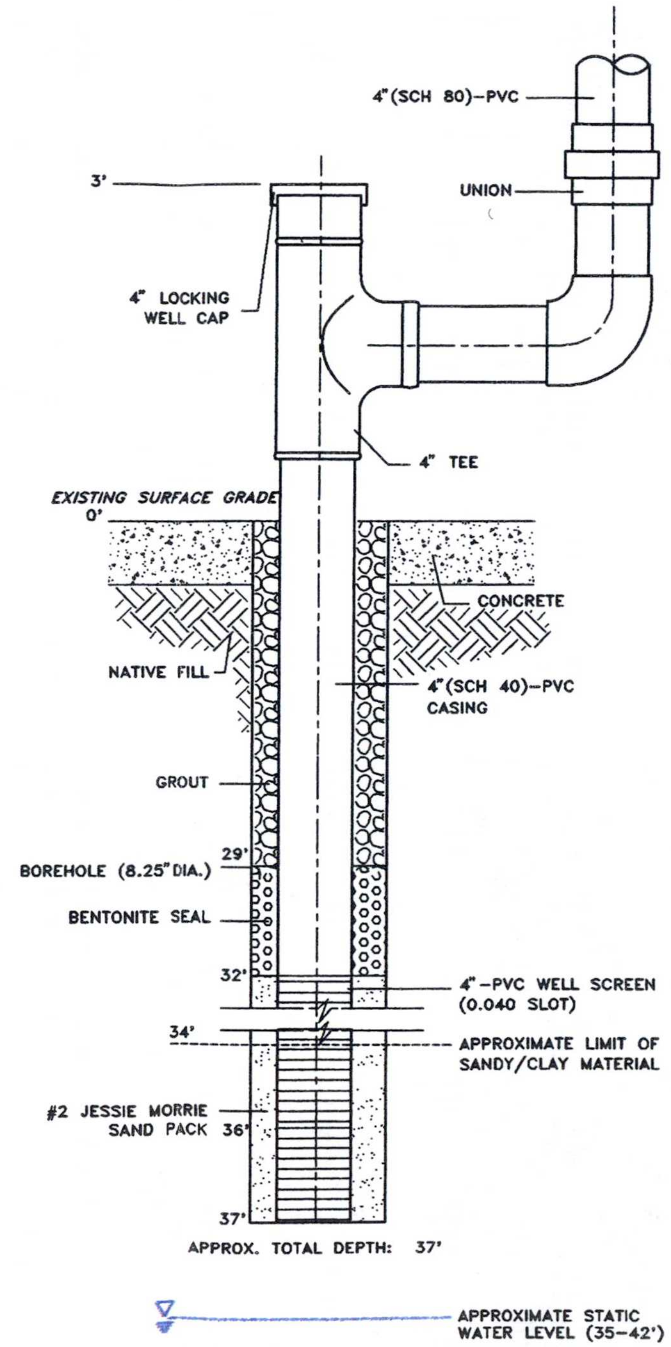
AIR SPARGE POINT DETAILS AND AIR SPARGE PIPING

DESIGNED BY: JAC/TES	DETAILED BY: VK	CHECKED BY: TES
DRAWING DATE: 3/16/95	FILE: 0076ASP1	
PROJECT NO.: 04100-0076	CONTRACT:	
DRAWING: Y2	REVISION: 1	

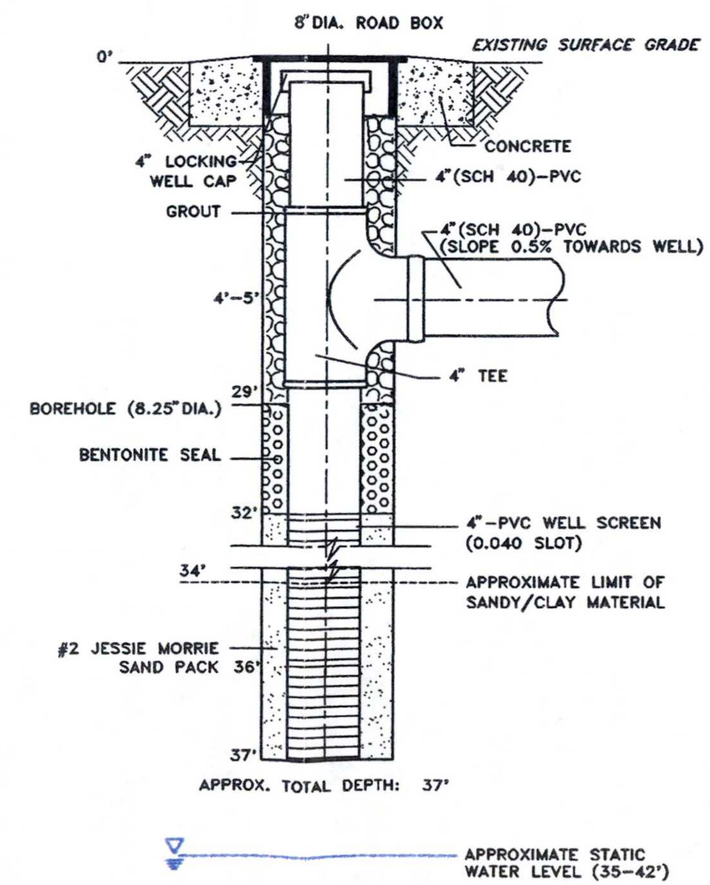
NO.	DATE	BY	REVISION
1	3/10/95	TES	REGULATORY REVIEW AND COLLECTION OF ADDITIONAL SITE DATA



SITE LAYOUT
SOIL VAPOR EXTRACTION SYSTEM
(DEEP WELLS)



PROPOSED DEEP SOIL VAPOR EXTRACTION WELL
INTERIOR (TYP. OF 5)
(SVE-14,15,16,17 & 20)
SCALE: NOT TO SCALE



PROPOSED DEEP SOIL VAPOR EXTRACTION WELL
EXTERIOR (TYP. OF 2)
(SVE-18 & 19)
SCALE: NOT TO SCALE

NOTES:
1. SEAL PIPING PENETRATIONS WITH NON-SHRINK GROUT.
2. NUMBERS TO THE LEFT OF THE WELL DETAILS INDICATE APPROXIMATE DEPTH OF THE VARIOUS MATERIALS FOR WELL CONSTRUCTION BELOW GRADE.
3. DEPTH OF FITTING AND PIPING MAY VARY ACCORDING TO ACTUAL GRADE AND SPECIFIED SLOPE OF PIPE. TO BE VERIFIED IN THE FIELD.

LEGEND

- MONITORING WELL
- RECOVERY WELL
- SOIL VAPOR EXTRACTION WELL (DEEP)
  EX.: SVE-18 - WELL IDENTIFICATION
- 4" DIA. UNDERGROUND SOIL VAPOR EXTRACTION PIPING
- 4" DIA. ABOVEGROUND SOIL VAPOR EXTRACTION PIPING
- SYSTEM PIPING TRENCH

NOTE:
1. MONITORING WELL LOCATIONS TRANSFERRED FROM PREVIOUS INVESTIGATION SITE MAP. WELL LOCATIONS NOT SURVEYED.
2. FOR TRENCH CROSS-SECTION A-A SEE DWG. Y5-1

SOURCE:
WHEELING PITTSBURGH STEEL CORPORATION

SCALE: 20 0 20 40 FEET

SIGNATURE	DATE
REVIEW ENGR:	
PROJECT ENGR:	
PROJECT MGR:	
CLIENT:	

GROUNDWATER TECHNOLOGY
100 RIVER RIDGE DRIVE
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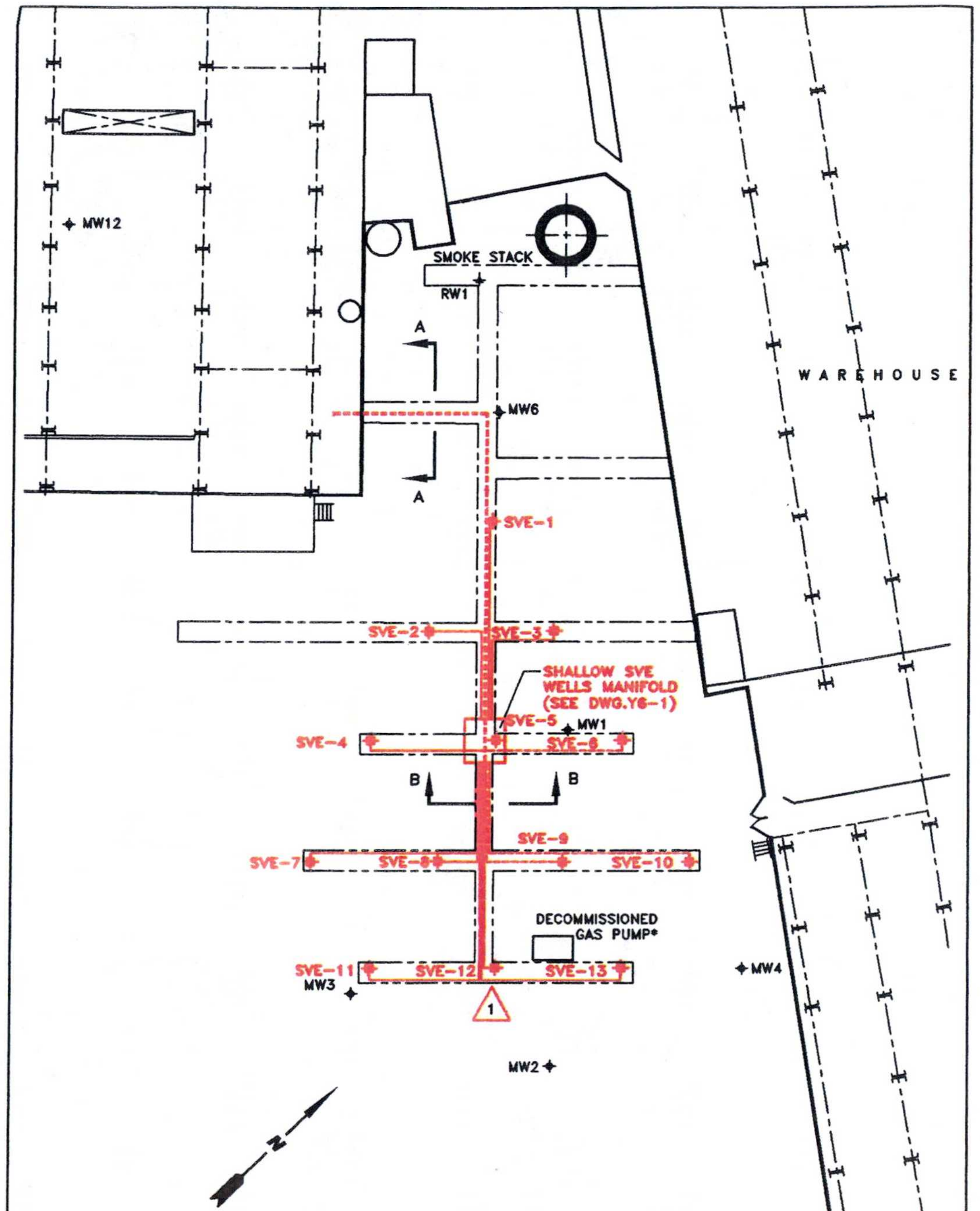
(617) 769-7600

WHEELING PITTSBURGH STEEL CORPORATION
MARTINS FERRY, OHIO
PLANT No.1
SOIL VAPOR EXTRACTION AND AIR SPARGING SYSTEM

SOIL VAPOR EXTRACTION WELL DETAILS AND SOIL VAPOR EXTRACTION PIPING (DEEP WELLS)

DESIGNED BY:	DETAILED BY:	CHECKED BY:
JAC/TES	VK	TES

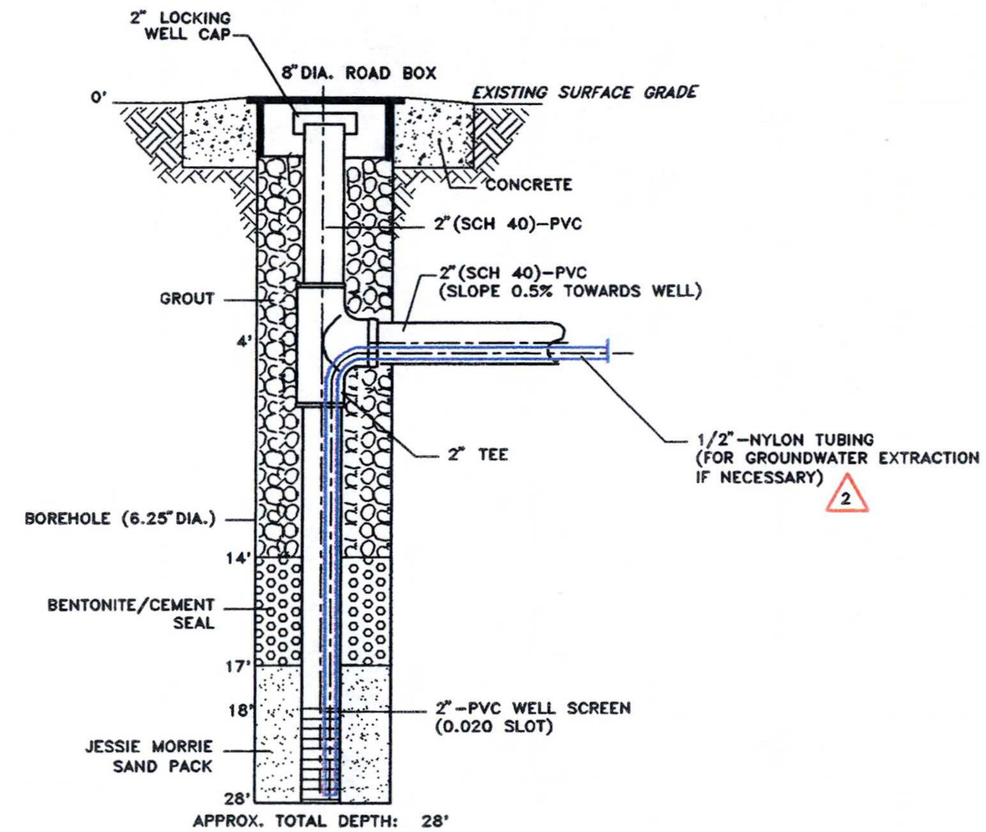
DRAWING DATE:	FILE:
3/16/95	0076SVDT
PROJECT NO.: 04100-0076	CONTRACT:
DRAWING: Y3	REVISION: 1



SITE LAYOUT

SOIL VAPOR EXTRACTION SYSTEM

(SHALLOW WELLS)



APPROXIMATE LIMIT OF SANDY/CLAY MATERIAL (34')

PROPOSED SHALLOW SOIL VAPOR EXTRACTION WELL
(TYP. OF 13)

SCALE: NOT TO SCALE

NOTES:

1. SEAL PIPING PENETRATIONS WITH NON-SHRINK GROUT.
2. NUMBERS TO THE LEFT OF THE WELL DETAILS INDICATE APPROXIMATE DEPTH OF THE VARIOUS MATERIALS FOR WELL CONSTRUCTION BELOW GRADE.
3. DEPTH OF FITTING AND PIPING MAY VARY ACCORDING TO ACTUAL GRADE AND SPECIFIED SLOPE OF PIPE. TO BE VERIFIED IN THE FIELD.

NO.	DATE	BY	REVISION
1.	3/10/95	TES	REGULATORY REVIEW ~~AND COLLECTION OF~~ ADDITIONAL SITE DATA
2.	4/19/95	MED	ADDITION OF GROUNDWATER EXTRACTION SYSTEM

LEGEND

MONITORING WELL

RECOVERY WELL

SOIL VAPOR EXTRACTION WELL (SHALLOW)
EX.: SVE-1 – WELL IDENTIFICATION.

4" DIA. UNDERGROUND SOIL VAPOR EXTRACTION PIPING

2" DIA. UNDERGROUND SOIL VAPOR EXTRACTION PIPING

2" DIA. ABOVEGROUND SOIL VAPOR EXTRACTION PIPING

SYSTEM PIPING TRENCH

SOURCE:
WHEELING PITTSBURGH STEEL CORPORATION

20 0 20 40
SCALE FEET

SIGNATURE	DATE
REVIEW ENGR:	
PROJECT ENGR:	
PROJECT MGR:	
CLIENT:	

GROUNDWATER TECHNOLOGY
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NORWOOD, MA 02062
(617) 769-7600

WHEELING PITTSBURGH STEEL CORPORATION

MARTINS FERRY, OHIO
PLANT No.1

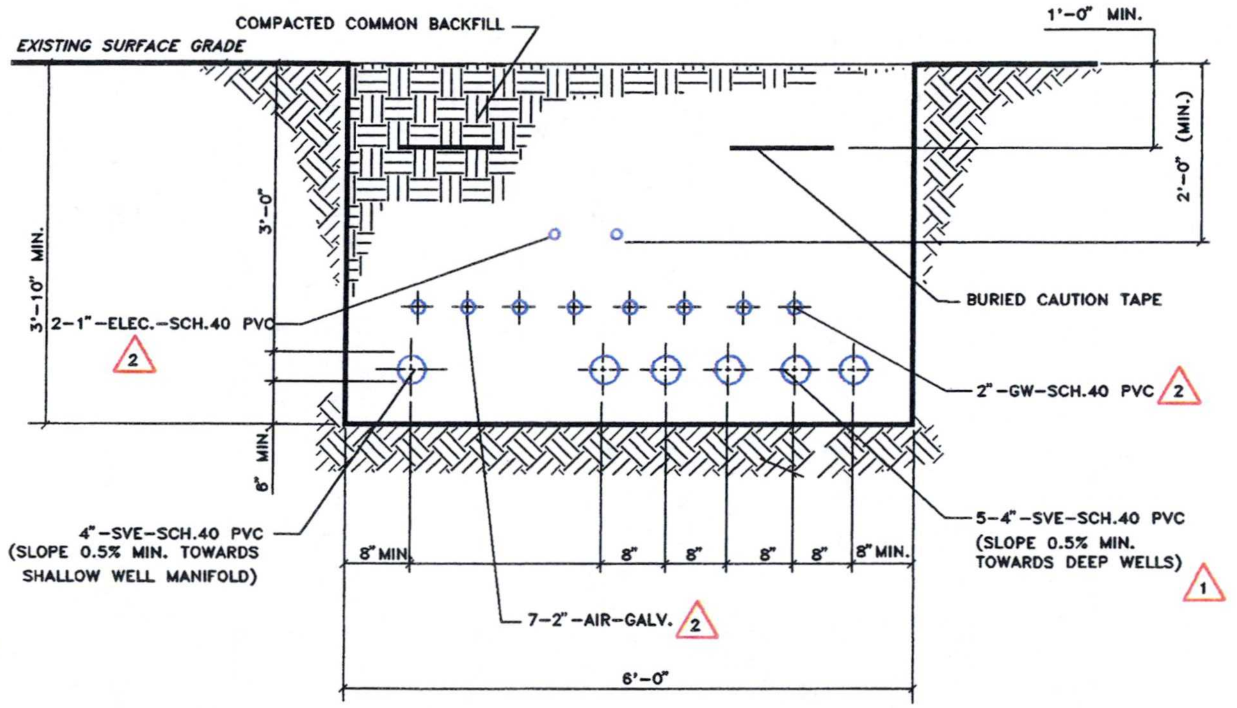
SOIL VAPOR EXTRACTION AND AIR SPARGING SYSTEM

SOIL VAPOR EXTRACTION WELL DETAIL AND SOIL VAPOR EXTRACTION PIPING (SHALLOW WELLS)

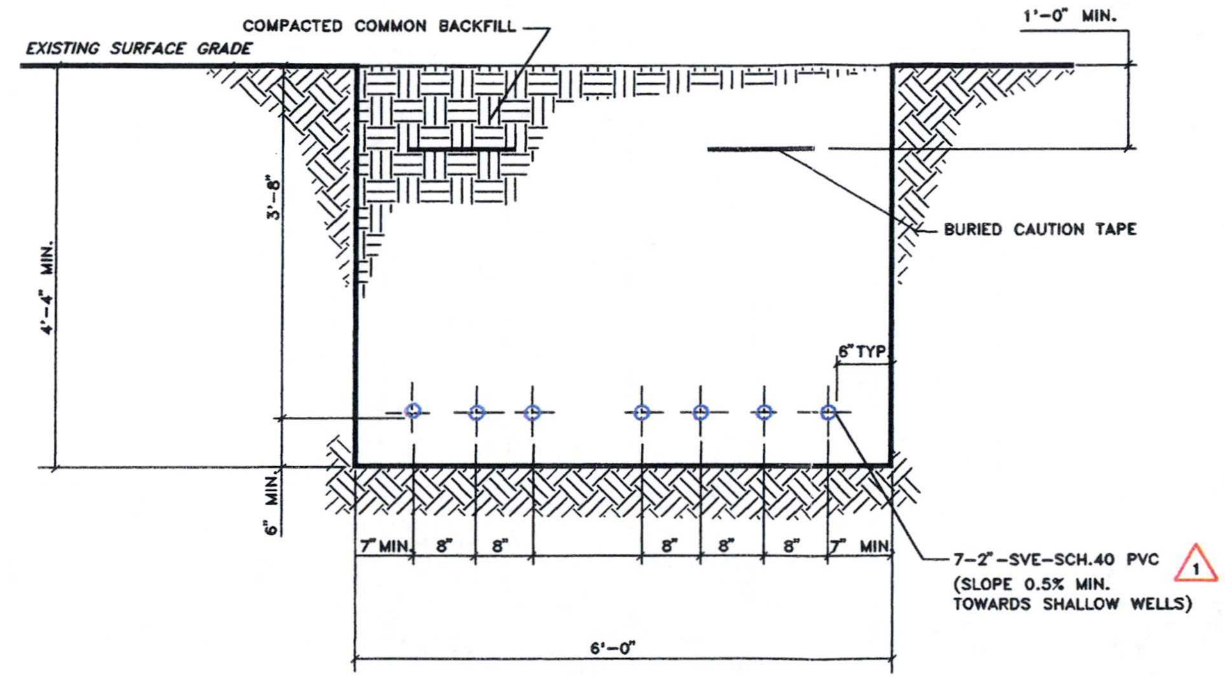
DESIGNED BY:	DETAILED BY:	CHECKED BY:
JAC/TES	VK	TES

DRAWING DATE:	FILE:
3/16/95	0076SVS2
PROJECT NO.:	CONTRACT:
04100-0076	
DRAWING:	REVISION:
Y4	2

NO.	DATE	BY	REVISION
1	3/10/95	TES	REGULATORY REVIEW [illegible] ADDITIONAL SITE DATA
2	4/19/95	MED	ADDITION OF ELECTRICAL AND GROUNDWATER LINES MODIFICATION OF SVE LINES



SYSTEM PIPING TRENCH CROSS-SECTION A-A



SYSTEM PIPING TRENCH CROSS-SECTION B-B

NOTES:

1. EXERCISE CAUTION EXCAVATING AROUND EXISTING WELL. EXCAVATE BY HAND ADJACENT TO WELL RISER.
2. RE-USE EXCAVATED MATERIALS FOR COMMON BACKFILL IF THEY ARE SUITABLE FRIABLE SOILS CONTAINING, NO SOD, STUMPS, STICKS ORGANIC MATTER, FROZEN MATERIALS, FREE WATER, PVM'T OR STONES GREATER THAN 4 INCHES. COMPACT BACKFILL IN MAX. 6 INCH LAYERS USING AT LEAST TWO PASSES OF A MECHANICAL COMPACTOR, EXCEPT ADJACENT TO & WITHIN 18 INCHES ABOVE CONDUITS WHERE COMPACTION SHALL BE BY HAND TAMPING. IF EXCAVATED SOILS DO NOT MEET REQUIREMENTS FOR COMMON BACKFILL, REPLACE WITH GRAVEL, AS SPECIFIED.

SCALE 1 0 1 2 FEET

SIGNATURE	DATE
REVIEW ENGR:	
PROJECT ENGR:	
PROJECT MGR:	

GROUNDWATER TECHNOLOGY

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WHEELING PITTSBURGH STEEL CORPORATION

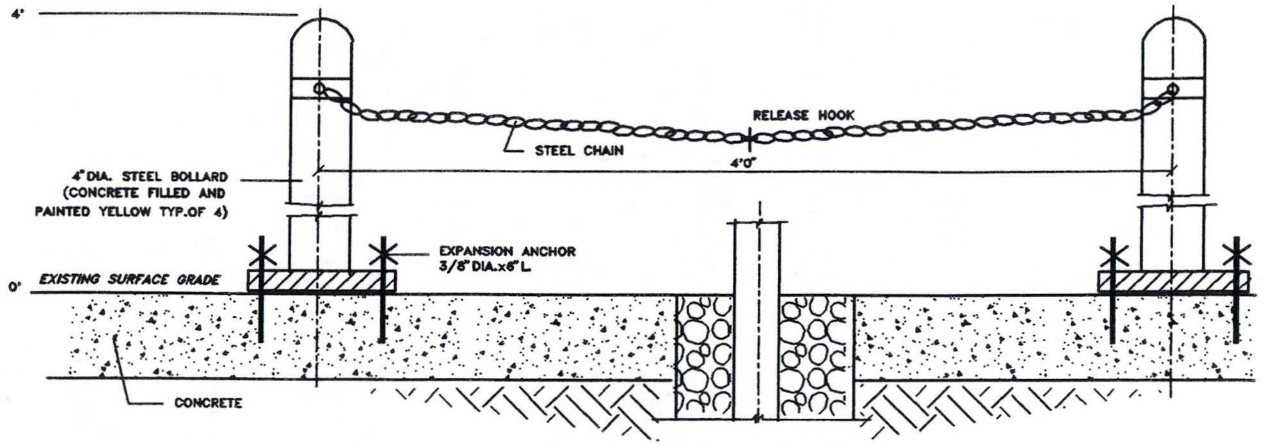
MARTINS FERRY, OHIO
PLANT No.1

SOIL VAPOR EXTRACTION AND AIR SPARGING SYSTEM

SYSTEM PIPING TRENCH CROSS-SECTIONS

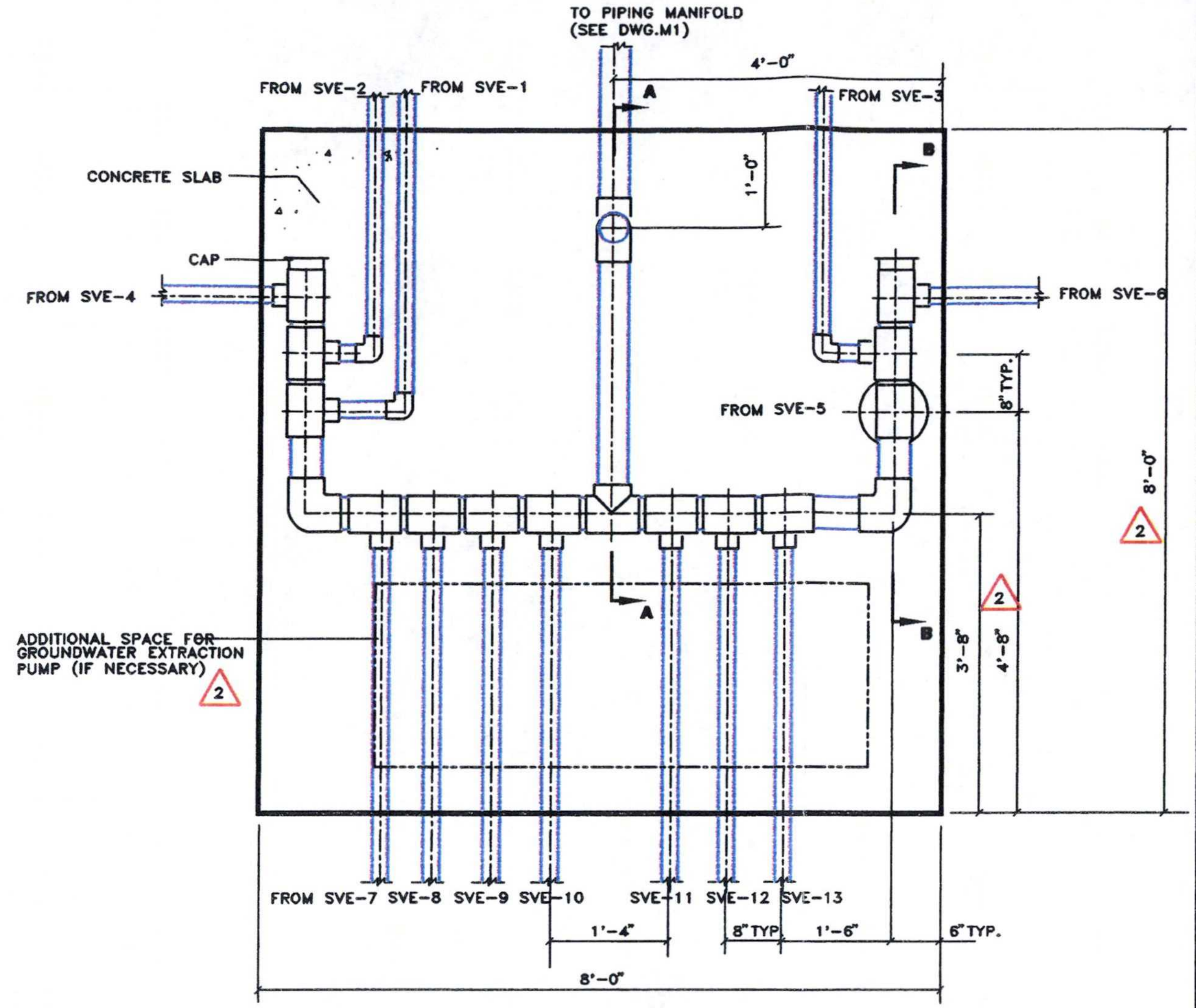
DESIGNED BY:	DETAILED BY:	CHECKED BY:
JAC/TES	VK	TES
DRAWING DATE: 4/19/95	FILE: 0076SCT2	
PROJECT NO.: 04100-0076	CONTRACT:	
DRAWING: Y5	REVISION: 2	

NO.	DATE	BY	REVISION
1.	3/10/95	TES	REGULATORY REVIEW AND COLLECTION OF ADDITIONAL SITE DATA
2.	4/19/95	MED	ADDITION OF GROUNDWATER EXTRACTION MODIFICATIONS

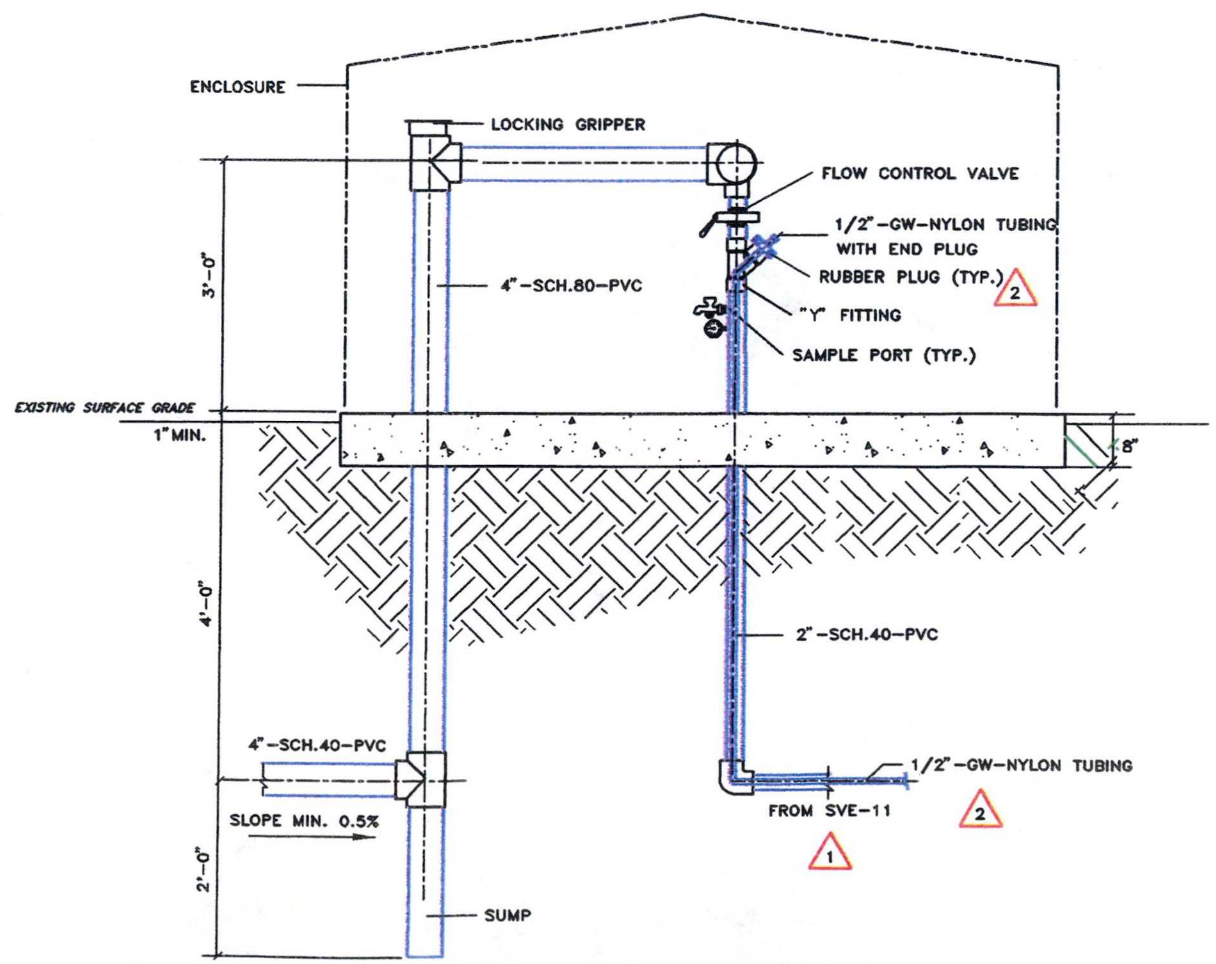


INTERIOR WELL HEAD PROTECTION ELEVATION (TYPICAL OF 12)

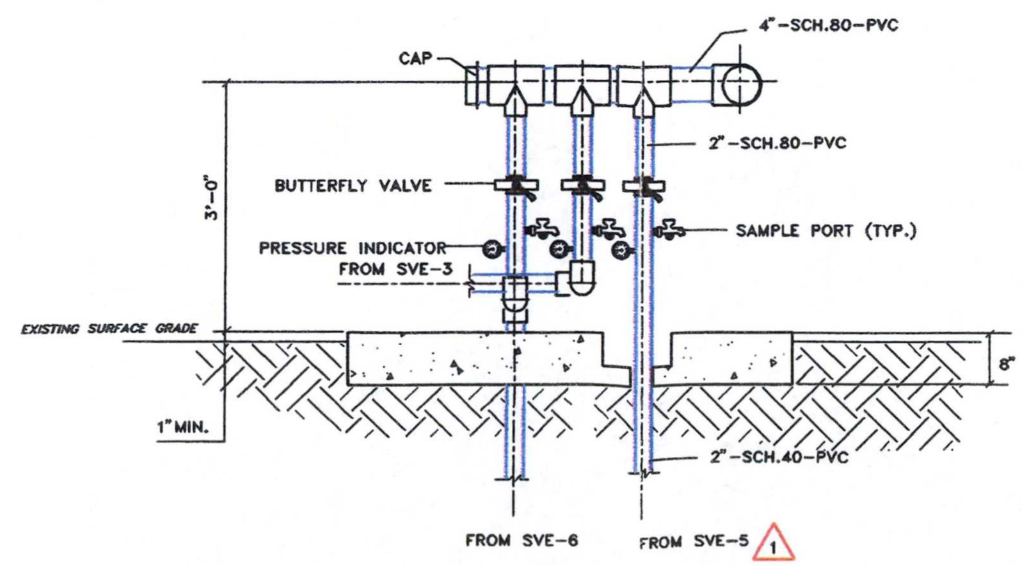
(ASP-1,2,3,6,7,8,10 & SVE-14,15,16,17,20)
SCALE: NOT TO SCALE



SHALLOW SOIL VAPOR EXTRACTION PIPING MANIFOLD PLAN VIEW



SHALLOW SOIL VAPOR EXTRACTION PIPING MANIFOLD CROSS-SECTION A-A



SHALLOW SOIL VAPOR EXTRACTION PIPING MANIFOLD CROSS-SECTION B-B

SCALE 1 0 1 2 FEET

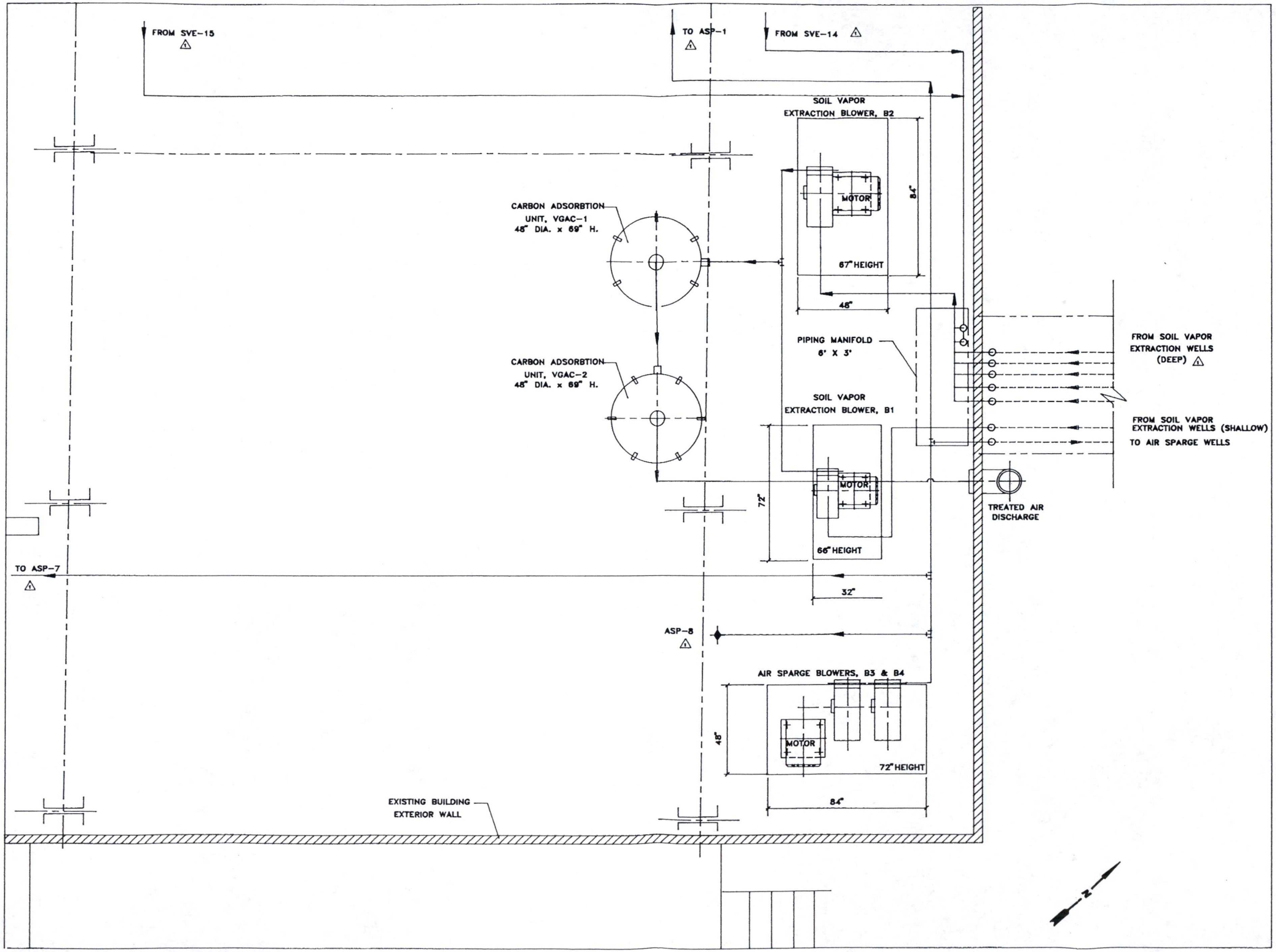
SIGNATURE	DATE
REVIEW ENGR:	
PROJECT ENGR:	
PROJECT MGR:	

GROUNDWATER TECHNOLOGY
100 RIVER RIDGE DRIVE
NORWOOD, MA 02062
(617) 769-7600

WHEELING PITTSBURGH STEEL CORPORATION
MARTINS FERRY, OHIO
PLANT No.1
SOIL VAPOR EXTRACTION AND AIR SPARGING SYSTEM

SYSTEM PIPING TRENCH CROSS-SECTIONS AND CONSTRUCTION DETAILS

DESIGNED BY:	DETAILED BY:	CHECKED BY:
TES/MED	VK	TES
DRAWING DATE: 4/19/95	FILE: 0076DET2	
PROJECT NO.: 04100-0076	CONTRACT:	
DRAWING: Y6	REVISION: 2	



NO.	DATE	BY	REVISION
1	3/10/95	TES	REGULATORY REVIEW AND COLLECTION OF ADDITIONAL SITE DATA

SYSTEM PIPING TRENCH
UNDERGROUND PIPE
ABOVEGROUND PIPE

SCALE 2 0 2 4 FEET

SIGNATURE	DATE
REVIEW ENGR:	
PROJECT ENGR:	
PROJECT MGR:	
CLIENT:	

GROUNDWATER TECHNOLOGY
100 RIVER RIDGE DRIVE
NORWOOD, MA 02062
(617) 769-7600

WHEELING PITTSBURGH STEEL CORPORATION

MARTINS FERRY, OHIO
PLANT No.1

SOIL VAPOR EXTRACTION AND AIR SPARGING SYSTEM

TREATMENT EQUIPMENT LAYOUT

DESIGNED BY: JAC/TES	DETAILED BY: VK	CHECKED BY: TES
DRAWING DATE: 3/13/95	FILE: 0076PLN1	
PROJECT NO.: 04100-0076	CONTRACT:	
DRAWING: M1	REVISION: 1	

NO.	DATE	BY	REVISION

VALVE AND PIPING SYMBOLS

- GLOBE VALVE
- GATE VALVE
- BUTTERFLY VALVE
- CHECK VALVE
- PLUG VALVE
- 3-WAY VALVE
- ANGLE VALVE
- RELIEF OR SAFETY VALVE
- DIAPHRAGM VALVE
- BALL VALVE
- GLOBE VALVE
- SELF-CONTAINED PRESSURE REGULATING VALVE W/RELIEF
- KNIFE GATE VALVE
- BP BACKFLOW PREVENTER
- NO NORMALLY OPEN
- NC NORMALLY CLOSED
- SP SAMPLE PORT
- FLEXIBLE HOSE
- BASKET TYPE STRAINER
- Y-TYPE STRAINER
- DUPLEX STRAINER
- SLEEVE COUPLING (SC)
- FLOOR DRAIN
- EQUIPMENT DRAIN
- CLEANOUT (CO)
- REMOVABLE PLUG
- REMOVABLE CAP
- BF BLIND FLANGE
- EXHAUST TO ATMOSPHERE (INSIDE)
- EXHAUST TO ATMOSPHERE (OUTSIDE)
- REDUCER
- UNION
- QUICK DISCONNECT COUPLING
- GAUGE SEAL
- DAMPER

VALVE OPERATOR SYMBOLS

- S SOLENOID
- M MOTOR, ELECTRIC
- DIAPHRAGM
- DIAPHRAGM WITH POSITIONER
- HANDWHEEL OR LEVER
- CHAINWHEEL

PRIMARY ELEMENT SYMBOLS - FLOW

- ORIFICE PLATE
- PITOT TUBE
- AVERAGING PITOT TUBE
- VENTURI OR FLOW TUBE
- TOTALIZING FLOWMETER
- FLUME
- WEIR
- TURBINE OR PROPELLOR TYPE METER
- MAGNETIC FLOW METER
- ROTAMETER

EQUIPMENT SYMBOLS

- SUBMERSIBLE PUMP
- PUMP
- PNEUMATIC DIAPHRAGM PUMP
- BLOWER
- AIR COMPRESSOR

GENERAL INSTRUMENT SYMBOLS

ONE VARIABLE — TWO VARIABLES

- LOCALLY MOUNTED
- PANEL MOUNTED
- REAR-OF-PANEL MOUNTED
- I INTERLOCK
- P PURGE

LINE SYMBOLS

- PROCESS PIPES OR CHANNELS
- CONNECTION TO PROCESS, MECHANICAL LINK OR INSTRUMENT SUPPLY
- PNEUMATIC SIGNAL
- ELECTRIC SIGNAL
- CAPILLARY TUBING (FILLED SYSTEM)
- HYDRAULIC SIGNAL
- ELECTROMAGNETIC OR SONIC SIGNAL NO WIRING OR TUBING

INSTRUMENT IDENTIFICATION TABLE

	FIRST LETTER		SUCCEEDING LETTERS		
	MEASURED OR INITIATING VARIABLE	MODIFIER	READOUT OR PASSIVE FUNCTION	OUTPUT FUNCTION	MODIFIER
A	ANALYSIS		ALARM		
B	BURNER FLAME				
C	CONDUCTIVITY			CONTROL	
D	DENSITY (SP. GR.)	DIFFERENTIAL			
E	VOLTAGE		PRIMARY ELEMENT		
F	FLOW RATE	RATIO			
G	GAUGING (DIMENSIONAL)		GLASS		
H	HAND (MANUAL)				HIGH
I	CURRENT		INDICATE		
J	POWER	SCAN			
K	TIME OR SCHEDULE			CONTROL STATION	
L	LEVEL		LIGHT (PILOT)		LOW
M	MOISTURE OR HUMIDITY				MIDDLE
N					
O			ORIFICE		
P	PRESSURE OR VACUUM		POINT (TEST)		
Q	QUANT. OR EVENT	INTEGRATE			
R	RADIOACTIVITY		RECORD OR PRINT		
S	SPEED OR FREQ.	SAFETY		SWITCH	
T	TEMPERATURE			TRANSMIT	
U	MULTIVARIABLE		MULTIFUNCTION		
V	VISCOSITY			VALVE OR DAMPER	
W	WEIGHT OR FORCE		WELL		
X	UNCLASSIFIED		UNCLASSIFIED		
Y				RELAY OR COMPUTE	
Z	POSITION			DRIVE, ACTUATE	

PROCESS LINE ABBREVIATIONS

AIR	AIR, ATMOSPHERIC PRESSURE
BW	BACKWASH
CA	COMPRESSED AIR
CGW	CONTAMINATED GROUNDWATER
D	DRAIN
EFF	EFFLUENT
EXH	EXHAUST
GW	GROUNDWATER
NPW	NON-POTABLE WATER
P	PRODUCT
PW	POTABLE WATER
S	SANITARY
SL	SLUDGE
SP	SAMPLE PORT
SS	STORM SEWER
SVE	SOIL VAPOR
TF	TOTAL FLUIDS
V	VENT
VAP	VAPOR

PIPING MATERIAL IDENTIFICATION

CPVC	CHLORINATED POLYVINYL CHLORIDE
CSP	CARBON STEEL PIPE
COP	COPPER
CMP	CORRUGATED METAL PIPE
CIP	CAST IRON PIPE
DIP	DUCTILE IRON PIPE
GAL	GALVANIZED STEEL PIPE
PE	POLYETHYLENE PIPE
PP	POLYPROPYLENE PIPE
PVC	POLYVINYL CHLORIDE PIPE
RCP	REINFORCED CONCRETE PIPE
HOSE	RUBBER HOSE
SS	STAINLESS STEEL PIPE
VCP	VITRIFIED CLAY PIPE

PROCESS PIPING IDENTIFICATION

PROCESS PIPE
PIPE DIAMETER (INCHES)
XXX-YY-Z
INSULATION CLASS
PIPING DESIGN TABLE NUMBER
PROCESS LINE ABBREVIATION

INSTRUMENT IDENTIFICATION

FIT 100A
FIT-100A
SUFFIX (NOT NORMALLY USED)
LOOP NUMBER
SUCCEEDING LETTERS
FIRST LETTER

FUNCTION ABBREVIATIONS

DO	DISSOLVED OXYGEN	OC	OPEN-CLOSE
FC	FAIL CLOSED	OO	ON-OFF (MAINTAINED)
FI	FAIL INDETERMINATE	ORP	OXIDATION REDUCTION POTENTIAL
FL	FAIL LOCKED	OSC	OPEN-STOP-CLOSE (MOMENTARY)
FO	FAIL OPEN	SS	START-STOP (MOMENTARY)
HOA	HAND-OFF-AUTOMATIC	>	HIGH SELECT
I/I	CURRENT-TO-CURRENT	<	LOW SELECT
I/P	CURRENT-TO-PNEUMATIC	$\sqrt{}$	SQUARE ROOT
LEL	LOWER EXPLOSIVE LIMIT	Σ	ADD OR TOTALIZE
LR	LOCAL-REMOTE		

APPROVALS

SIGNATURE	DATE
REVIEW ENGR:	
PROJECT ENGR:	
PROJECT MGR:	
CLIENT:	

GROUNDWATER TECHNOLOGY
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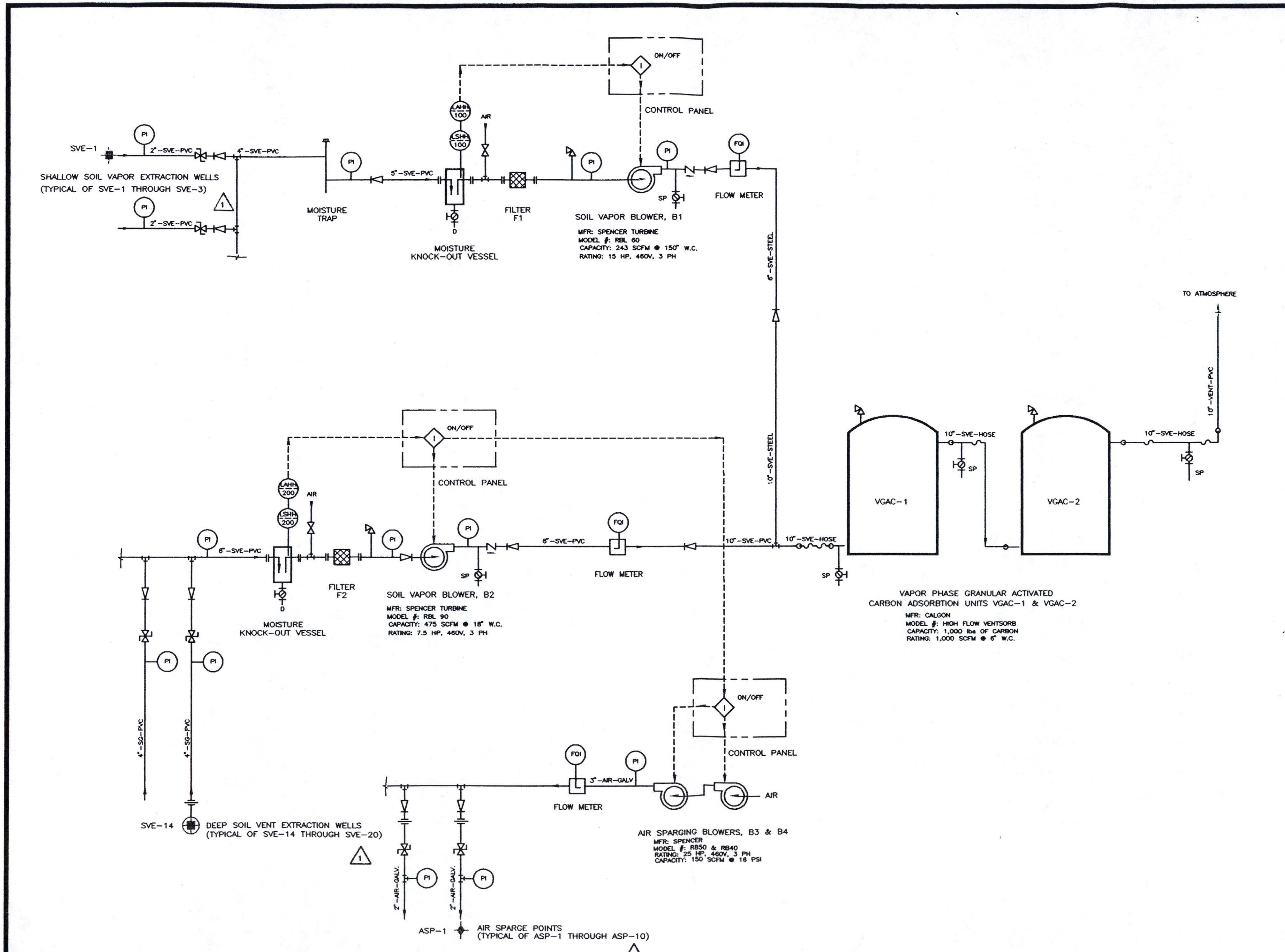
WHEELING PITTSBURGH STEEL CORPORATION
MARTINS FERRY, OHIO
PLANT No.1
SOIL VAPOR EXTRACTION AND AIR SPARGING SYSTEM

PIPING & INSTRUMENTATION DIAGRAM LEGEND

DESIGNED BY:	DETAILED BY:	CHECKED BY:
JAC	VK	TES

DATE: 6/24/94	FILE: 0076PLEG
PROJECT NO.: 04100-0076	CONTRACT:
DRAWING: P1	REVISION:



NO.	DATE	BY	REVISION
1	3/10/95	TES	REGULATORY REVIEW AND COLLECTION OF ADDITIONAL SITE DATA

SIGNATURE	DATE
REVIEW ENGR:	
PROJECT ENGR:	
PROJECT MGR:	
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WHEELING PITTSBURGH STEEL CORPORATION

MARTINS FERRY, OHIO
PLANT No.1

SOIL VAPOR EXTRACTION AND AIR SPARGING SYSTEM

PIPING & INSTRUMENTATION DIAGRAM

DESIGNED BY:	DETAILED BY:	CHECKED BY:
JACTES	VK	TES
DRAWING DATE: 4/26/95	FILE: 0076PID1	
PROJECT NO.: 04100-0076	CONTRACT:	
DRAWING: P2	REVISION: 1	

ONE-LINE DIAGRAM SYMBOLS

- CIRCUIT AND EQUIPMENT INSTALLED BY THIS CONTRACT
- EQUIPMENT ENCLOSURE
- CONTROL OR INTERLOCK CIRCUIT
- CONNECTION
- MOLDED CASE CIRCUIT BREAKER
- FUSE
- FUSED DISCONNECT SWITCH
- FULL VOLTAGE, NON-REVERSING (FVNR) MAGNETIC MOTOR STARTER
- MANUAL MOTOR STARTER
- AS — AMMETER SWITCH
- VS — VOLTMETER SWITCH
- A — AMMETER
- V — VOLTMETER
- RECEPTACLE-CLASS I, DIVISION 1, GROUPS C, D
- FUSED POTENTIAL TRANSFORMERS
- CURRENT TRANSFORMER
- POWER TRANSFORMER
- LIGHTNING OR SURGE ARRESTER
- GROUND CONNECTION
- KWH — KW-HOUR METER SOCKET. METER FURNISHED BY UTILITY.
- 5 — MOTOR - NUMBER INDICATES HP

PLAN SYMBOLS

- NEW CONSTRUCTION
- EXISTING CONSTRUCTION
- EXISTING CONSTRUCTION TO BE REMOVED
- CONDUIT EXPOSED
- CONDUIT CONCEALED IN WALL CEILING OR HIDDEN FROM VIEW
- CONDUIT CONCEALED IN FLOOR OR UNDERGROUND
- FLEXIBLE CONDUIT (LIQUID TIGHT)
- GROUND CABLE
- BOLTED GROUND CONNECTION
- WELDED GROUND CONNECTION
- GROUND ROD
- HOMERUN. ARROWHEADS INDICATE NUMBER OF CIRCUITS
- CONDUIT TURNING UP
- CONDUIT TURNING DOWN
- CONDUIT WITH BUSHING
- CONDUIT TERMINATED OR CAPPED
- POWER PANEL-480V, 3ø
- LIGHTING PANEL-120/240V, 1ø OR 208/120, 3ø
- DISCONNECT (SAFETY) SWITCH
- MS — MANUAL MOTOR STARTER
- MAGNETIC MOTOR STARTER
- COMBINATION MAGNETIC MOTOR STARTER
- 5 — MOTOR (NUMBER INDICATES HP)
- P — PULLBOX
- J — JUNCTION BOX
- EXIT LIGHT
- L-1 — FLUORESENT LUMINAIRE TYPE L-1
- L-1 — INCANDESCENT OR H.I.D. LUMINAIRE TYPE L-1
- EMEGENCY LIGHTING UNIT
- EMERGENCY FLUORESENT LIGHTING FIXTURE
- DUPLEX RECEPTACLE WP-WEATHERPROOF GFCI-GROUND FAULT CIRCUIT INTERRUPTER
- RECEPTACLE-CLASS I, DIVISION 1, GROUPS C, D
- T — THERMOSTAT
- S — SINGLE POLE SWITCH
- S3 — THREE-WAY POLE SWITCH
- S4 — FOUR-WAY POLE SWITCH

SCHEMATIC DIAGRAM SYMBOLS

- TERMINAL
- CONDUCTOR CONNECTION
- NO CONNECTION
- CONTACT NORMALLY OPEN (NO)
- CONTACT NORMALLY CLOSE (NC)
- SWITCH
- SELECTOR SWITCH
- PUSHBUTTON-NORMALLY OPEN MOMENTARY
- PUSHBUTTON-NORMALLY CLOSED MOMENTARY
- PRESSURE OR VACUUM SWITCH-CLOSES WITH INCREASING PRESSURE OR DECREASING VACUUM
- PRESSURE OR VACUUM SWITCH-OPENS WITH INCREASING PRESSURE OR DECREASING VACUUM
- FLOW SWITCH-CLOSES WITH INCREASING FLOW
- LIMIT SWITCH NC
- LIMIT SWITCH NC-HELD OPEN
- NO TIME DELAY CONTACT. TIME DELAY CLOSING AFTER ENERGIZATION
- NC TIME DELAY CONTACT. TIME DELAY OPENING AFTER ENERGIZATION
- NO TIME DELAY CONTACT. TIME DELAY OPENING AFTER DE-ENERGIZATION
- NC TIME DELAY CONTACT. TIME DELAY CLOSING AFTER DE-ENERGIZATION
- M — MOTOR STARTER COIL
- RELAY COIL
- G — INDICATING LIGHT-COLOR INDICATED
  - A-AMBER Y-YELLOW
  - BL-BLUE W-WHITE
  - G-GREEN
- SOLENOID VALVE COIL
- THERMAL OVERLOAD RELAY CONTACT
- FLOW SWITCH-OPENS WITH INCREASING FLOW
- LIQUID LEVEL SWITCH-CLOSES ON RISING LEVEL
- LIQUID LEVEL SWITCH-OPENS ON RISING LEVEL
- TEMPERATURE SWITCH-CLOSES ON RISING TEMPERATURES
- TEMPERATURE SWITCH-OPENS ON RISING TEMPERATURES
- LIMIT SWITCH NO
- LIMIT SWITCH NO-HELD CLOSED
- FUSE
- CONTROL POWER TRANSFORMER (CPT)
- GROUND
- H — HORN
- B — BELL

GENERAL ABBREVIATIONS

A, AUTO	AUTOMATIC
ACK	ACKNOWLEDGE
AFF	ABOVE FINISH FLOOR
AFG	ABOVE FINISH GRADE
BC	BARE COPPER
C	CONDUIT
CB	CIRCUIT BREAKER
CL	CLOSE
CPT	CONTROL POWER TRANSFORMER
CR	CONTROL RELAY
CS	CONTROL SWITCH
CT	CURRENT TRANSFORMER
DWG	DRAWING
ETM	ELAPSED TIME METER
FU	FUSE
FWD	FORWARD
GND	GROUND
H	HAND
HI	HIGH
HS	HIGH SPEED
IL	INDICATING LIGHT
INST	INSTANTANEOUS
L	LOW
LOC	LOCAL
LS	LOW SPEED
MAN	MANUAL
MCC	MOTOR CONTROL CENTER
NC	NORMALLY CLOSED
NL	NIGHT LIGHT (UNSWITCHED FIXTURE)
NO	NORMALLY OPEN
O	OFF
OL	THERMAL OVERLOAD RELAY
OP	OPEN
PB	PUSHBUTTON
PLC	PROGRAMMABLE LOGIC CONTROLLER
REM	REMOTE
REV	REVERSE
SOL	SOLENOID (OTHER THAN VALVE)
SP	SPARE
SS	SELECTOR SWITCH
SV	SOLENOID VALVE
T, T-STAT	THERMOSTAT
TDAE	TIME DELAY AFTER ENERGIZATION
TDAF	TIME DELAY AFTER DE-ENERGIZATION
TDR	TIME DELAY RELAY
TEMP	TEMPERATURE
TMR	TIMER
WP	WEATHERPROOF
XFMR	TRANSFORMER
XP	EXPLOSIONPROOF-CLASS I, DIVISION I, GROUPS C, D

NO.	DATE	BY	REVISION

SIGNATURE	DATE
ENG MGR:	
PROJECT ENGR:	
PROJECT MGR:	
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220 NORWOOD PARK SOUTH
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WHEELING PITTSBURGH STEEL CORPORATION

MARTINS FERRY, OHIO
PLANT No.1

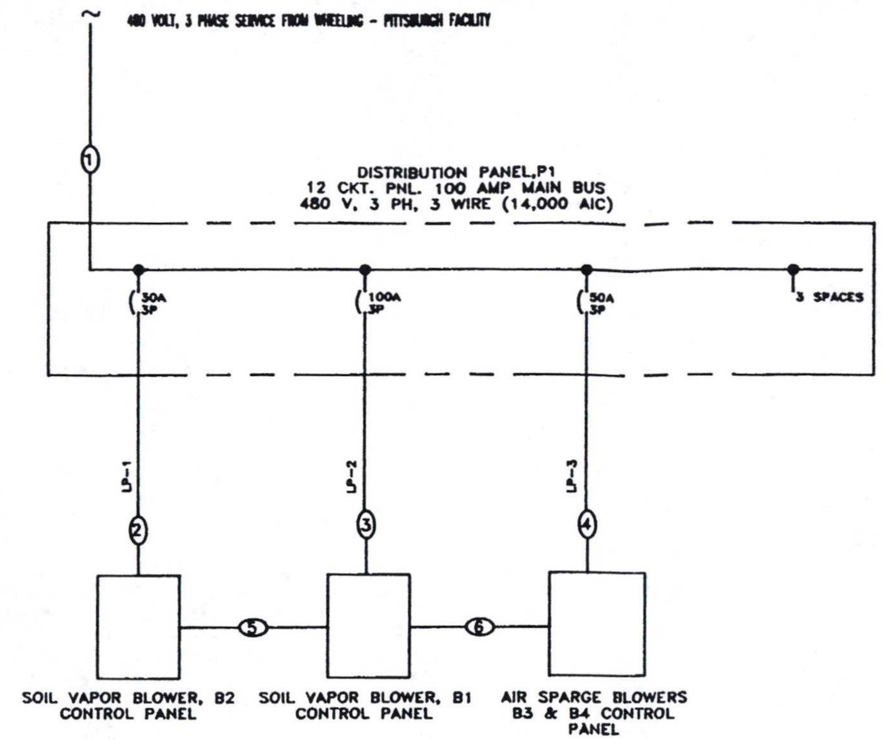
SOIL VAPOR EXTRACTION AND AIR SPARGING SYSTEM

ELECTRICAL DIAGRAM LEGEND

DESIGNED BY:	DETAILED BY:	CHECKED BY:
MM	VK	TES

DATE: 6/29/94	FILE: 0076ELEG
PROJECT NO.: 04100-0076	CONTRACT:
DRAWING: E1	REVISION: -

ONE - LINE



PANEL SCHEDULE

DISTRIBUTION PANEL, P1, 480 VOLT, 3 PHASE, 3 WIRE, 100 AMP

CIRCUIT NO.	POLE NO.	BREAKER TRIP	WIRE SIZE	GND WIRE	CONNECTED VA ϕA	CONNECTED VA ϕB	CONNECTED VA ϕC	SERVICE
LP-1	1	30A	12	12	9			SOIL VAPOR BLOWER, B2
	3					9		
	5						9	
LP-3	7	50A	10	10	17			AIR SPARGE BLOWERS B3 & B4
	9					17		
	11						17	
				SUB-TOTAL	26	26	26	

CIRCUIT NO.	POLE NO.	BREAKER TRIP	WIRE SIZE	GND WIRE	CONNECTED VA ϕA	CONNECTED VA ϕB	CONNECTED VA ϕC	SERVICE
LP-2	2	100	1	6	34			SOIL VAPOR BLOWER, B1
	4					34		
	6						34	
	8							
	10							
				SUB-TOTAL	34	34	34	

	ϕA	ϕB	ϕC
TOTAL CONNECTED VA	60	60	60
TOTAL DEMAND VA			

CONDUIT AND CABLE SCHEDULE

CONDUIT #	DESTINATION	ORIGIN	CONDUIT SIZE	CONDUCTORS
1	DIST. PANEL, P1	480V POWER SOURCE	1 1/2" C	3-#1 & 1-#6 GRD
2	SOIL VAPOR BLOWER, B2	DIST. PANEL P1	3/4" C	3-#12 & 1-#12 GRD
3	SOIL VAPOR BLOWER, B1	DIST. PANEL P1	1 1/2" C	3-#1 & 1-#6 GRD
4	AIR SPARGE BLOWERS, B3 & B4	DIST. PANEL P1	3/4" C	3-#10 & 1-#10 GRD
5	SOIL VAPOR BLOWER, B2	SOIL VAPOR BLOWER, B1	3/4" C	4-#14 (CONTROL)
6	SOIL VAPOR BLOWER, B1	SOIL VAPOR BLOWER, B2	3/4" C	4-#14 (CONTROL)

NO.	DATE	BY	REVISION

NOTE:

(1) IDENTIFIES THE CONDUIT AND CABLE DESIGNATION. REFER TO CONDUIT AND CABLE SCHEDULE FOR DETAILS.

	SIGNATURE	DATE
REVIEW ENGR:		
PROJECT ENGR:		
PROJECT MGR:		
CLIENT:		

GROUNDWATER TECHNOLOGY
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NORWOOD, MA 02062 (617) 769-7602

WHEELING PITTSBURGH STEEL CORPORATION

MARTINS FERRY, OHIO
PLANT No.1

SOIL VAPOR EXTRACTION AND AIR SPARGING SYSTEM

ELECTRICAL ONE-LINE DIAGRAM

DESIGNED BY: RI	DETAILED BY: VK	CHECKED BY: TES
DRAWING DATE: 6/30/94	FILE: 0076-ONE	
PROJECT NO.: 04100-0076	CONTRACT:	
DRAWING: E2	REVISION:	

HAZARDOUS AREA CLASSIFICATION LEGEND

–CLASS I DIVISION 1 (NOT SHOWN)

ANY SPACE BELOW GRADE – MONITORING WELLS, WELL VAULTS, AND SECTIONS OF THE TRENCH LESS THAN 20 FT. FROM CLASS I LOCATIONS.

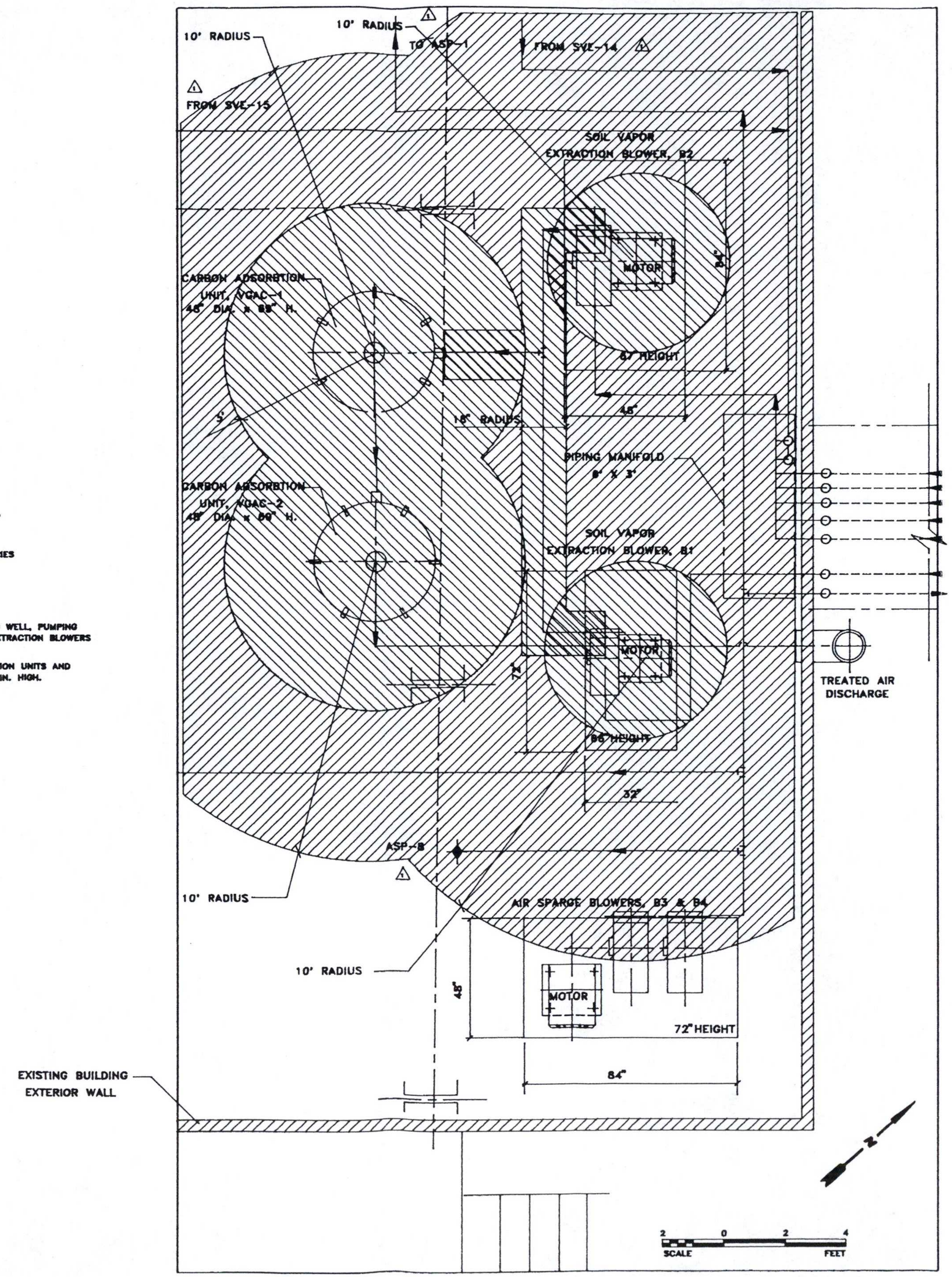
THE SPACE INSIDE OF ALL PIPING UNDER PRESSURE THAT CARRIES SOIL VAPOR, WHERE APPROPRIATE.

–CLASS I DIVISION 2

THE SPACE WITHIN A RADIUS OF 10 FT. FROM THE MONITORING WELL, PUMPING WELL, AROUND CARBON ADSORBTION UNITS AND SOIL VAPOR EXTRACTION BLOWERS EXTENDING UP TO 18 IN. ABOVE GRADE LEVEL.

THE SPACE WITHIN A RADIUS OF 3 FT. FROM CARBON ADSORBTION UNITS AND SOIL VAPOR EXTRACTION BLOWERS, WHICH EXTENDS ABOVE 18 IN. HIGH.

–NON CLASSIFIED



NO.	DATE	BY	REVISION
1	3/10/95	TES	REGULATORY REVIEW AND COLLECTION OF ADDITIONAL SITE DATA

LEGEND

- MONITORING WELL
- RECOVERY WELL
- AIR SPARGE POINT EX.: ASP-9 – POINT IDENTIFICATION.
- SOIL VAPOR EXTRACTION WELL (DEEP) EX.: SVE-18 – WELL IDENTIFICATION.
- SOIL VAPOR EXTRACTION WELL (SHALLOW) EX.: SVE-1 – WELL IDENTIFICATION.
- SYSTEM PIPING TRENCH
- UNDERGROUND PIPE
- ABOVEGROUND PIPE

NOTE:
1. MONITORING WELL LOCATIONS TRANSFERED FROM PREVIOUS INVESTIGATION SITE MAP. WELL LOCATIONS NOT SURVEYED.
SOURCE:
WHEELING PITTSBURGH STEEL CORPORATION

SIGNATURE	DATE
REVIEW ENGR:	
PROJECT ENGR:	
PROJECT MGR:	
CLIENT:	

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WHEELING PITTSBURGH STEEL CORPORATION
MARTINS FERRY, OHIO
PLANT No.1
SOIL VAPOR EXTRACTION AND AIR SPARGING SYSTEM

HAZARDOUS AREA CLASSIFICATION DIAGRAM

DESIGNED BY:	DETAILED BY:	CHECKED BY:
JAC/TES	VK	TES

DRAWING DATE:	FILE:
3/13/95	0076HAZ1
PROJECT NO.: 04100-0076	CONTRACT:
DRAWING: E3	REVISION: 1

SUPPORTING CALCULATIONS AND MODEL OUTPUTS

RESULTS OF VENT-ROI ANALYSIS

EFFECTIVE RADIUS CALCULATION FOR CONVENTIONAL SOIL VAPOR EXTRACTION SYSTEM

Wheeling Pittsburgh Steel site in Wheeling, West Virginia
System design for the lower lithology

Weathered Gasoline/JP-4 (contaminant mixture, volatile and biodegradable)

log10(MW P*)	= 1.34 - 3.19 δm
Temperature Constant	= 1904 deg K
Liquid Density	= .7 g/cc
Zero Order Bioremediation Rate Constant	= 5 ppm/day
Initial Total Soil Contaminant Concentration	= 185 ppm
Residual (Non-degradable) Soil Concentration	= 1 ppm

Vertical wells in 6.3 inch boreholes, extending to groundwater, screened from 30 to 39 feet

Thickness of Vented Soil Interval	= 5 feet
Slope of log10(P) vs Distance from Pilot Test	= .023 per ft
Soil Gas Temperature	= 50 deg F
Applied Vacuum	= 18 in. water column
Air Flow Rate per Vapor Extraction Well	= 68.8 scfm
Desired Time to Cleanup	= 365 days
Cleanup Goal	= 90 % removal

VOLATILIZATION:	SINGLE WELL EFFECTIVE RADIUS	= 20.95 FEET
	INSUFFICIENT SURFACE INFILTRATION FOR MULTIPLE WELL SYSTEM	
BIODEGRADATION:	SINGLE WELL RADIUS OF INFLUENCE	= 63.12 FEET
	INTERWELL RADIUS OF INFLUENCE	= 52.52 FEET
VOL. PLUS BIO.:	SINGLE WELL EFFECTIVE RADIUS	= 63.12 FEET
	INTERWELL EFFECTIVE RADIUS	= 52.52 FEET

ANALYSIS OF VACUUM DISSIPATION DATA FROM PILOT TEST

18 INCHES APPLIED VACUUM:

Monitoring Well	Distance from SVE Well (ft)	Measured Vacuum (inches w.c.)	log10(Vac)
DOP-1	12.8	.6	-.222
* DOP-2	4.7	.7	-.155
VMP-1	29	.53	-.276
VMP-2	22	.53	-.276
VMP-3	10.5	.7	-.155

* = outlier, not considered in analysis
Additional data point based on applied vacuum:
3.6 inches of water column at 0 feet from SVE well

Slope	= -.026 per foot
Intercept	= 2.07 inches of water column
R squared	= .673

12 INCHES APPLIED VACUUM:

Monitoring Well	Distance from SVE Well (ft)	Measured Vacuum (inches w.c.)	log10(Vac)
DOP-1	12.8	.4	-.398
DOP-2	4.7	.63	-.201
VMP-1	29	.38	-.42
VMP-2	22	.3	-.523
VMP-3	10.5	.47	-.328

Additional data point based on applied vacuum:
1.2 inches of water column at 0 feet from SVE well

Slope	= -.017 per foot
Intercept	= .83 inches of water column
R squared	= .695

8 INCHES APPLIED VACUUM:

Monitoring Well	Distance from SVE Well (ft)	Measured Vacuum (inches w.c.)	log10(Vac)
DOP-1	12.8	.3	-.523
* DOP-2	4.7	.32	-.495
VMP-1	29	.25	-.602
VMP-2	22	.2	-.699
VMP-3	10.5	.35	-.456

* = outlier, not considered in analysis
Additional data point based on applied vacuum:
1.6 inches of water column at 0 feet from SVE well

Slope = -.027 per foot
Intercept = .976 inches of water column
R squared = .716

Average slope from tests at 3 applied vacuums = -.023 per foot.

OBSERVED AND PREDICTED FLOW RESPONSE TO APPLIED VACUUM

	Applied Vacuum (inches w.c.)	Observed Flow Response (scfm)	Predicted Flow Response (scfm)	Relative Percent Difference
1.	18	69.8	68.83	-1.4 %
2.	12	52.3	52.79	.9 %
3.	8	38.1	38.29	.5 %

Mean Value of Relative Percent Difference:	0 %
Mean Absolute Value of Relative Percent Difference:	.9 %
Standard Deviation of Prediction:	.8 scfm
Soil Permeability in Horizontal Direction (sq cm):	7.94E-07
Standard Deviation of Soil Permeability Estimation (sq cm):	1E-08
Ratio of Horizontal to Vertical Permeability:	1.4

RESULTS OF VENT-ROI ANALYSIS

SOIL GAS EXTRACTION RATE FOR CONVENTIONAL SOIL VAPOR EXTRACTION SYSTEM

Wheeling Pittsburgh Steel site in Wheeling, West Virginia
Assumed Data for the sandy clay source area
System Design for the ~~lower~~ upper lithology.

Weathered Gasoline/JP-4 (contaminant mixture, volatile and biodegradable)

log10(MW P*)	= 1.34 - 3.19 ðm
Temperature Constant	= 1904 deg K
Liquid Density	= .7 g/cc
Zero Order Bioremediation Rate Constant	= 5 ppm/day
Initial Total Soil Contaminant Concentration	= 50 ppm
Residual (Non-degradable) Soil Concentration	= 1 ppm

Vertical wells in 6.3 inch boreholes, not extending to groundwater, screened from 20 to 30 feet
50 by 200 foot plume requires 13 wells, operated simultaneously,

Thickness of Vented Soil Interval	= 10 feet
Slope of log10(P) vs Distance from Pilot Test	= .08 per ft
Soil Gas Temperature	= 50 deg F
Interwell Effective Radius	= 18.2 feet
Single Well Effective Radius	= 20.9 feet
Desired Time to Cleanup	= 365 days
Cleanup Goal	= 90 % removal

FLOW REQUIRED FOR SINGLE WELL AT THESE CONDITIONS	= 20 scfm
APPLIED VACUUM REQUIRED TO ACHIEVE THIS FLOW	= 149.9 in. water column

TOTAL FLOW REQUIRED FOR MULTIWELL SYSTEM	= 226.65 scfm

GAC-USE

A PROGRAM FOR ESTIMATION OF GRANULAR ACTIVATE CARBON CONSUMPTION RATES

SUMMARY OF VAPOR PHASE GAC CONSUMPTION ANALYSIS

Wheeling-Pittsburgh Steel site in Martins Ferry, Ohio

Air flow rate	= 925 cfm
Influent air temperature	= 55 deg F
Temperature increase across blower	= 50 deg F

Influent vapor phase contaminant concentrations:

Benzene	= 0 ppmv .069	Toluene	= 0 ppmv .200
Ethylbenzene	= 0 ppmv .035	Xylene	= 0 ppmv .170

VAPOR PHASE CARBON CONSUMPTION = 675 lb/year

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Air flow rate	= 925 cfm
Influent air temperature	= 55 deg F
Temperature increase across blower	= 50 deg F

Influent vapor phase contaminant concentrations:

Benzene	= 0 ppmv .330	Toluene	= 0 ppmv .200
Ethylbenzene	= 0 ppmv .035	Xylene	= 0 ppmv .170

VAPOR PHASE CARBON CONSUMPTION = 1156 lb/year

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SUMMARY OF VAPOR PHASE GAC CONSUMPTION ANALYSIS

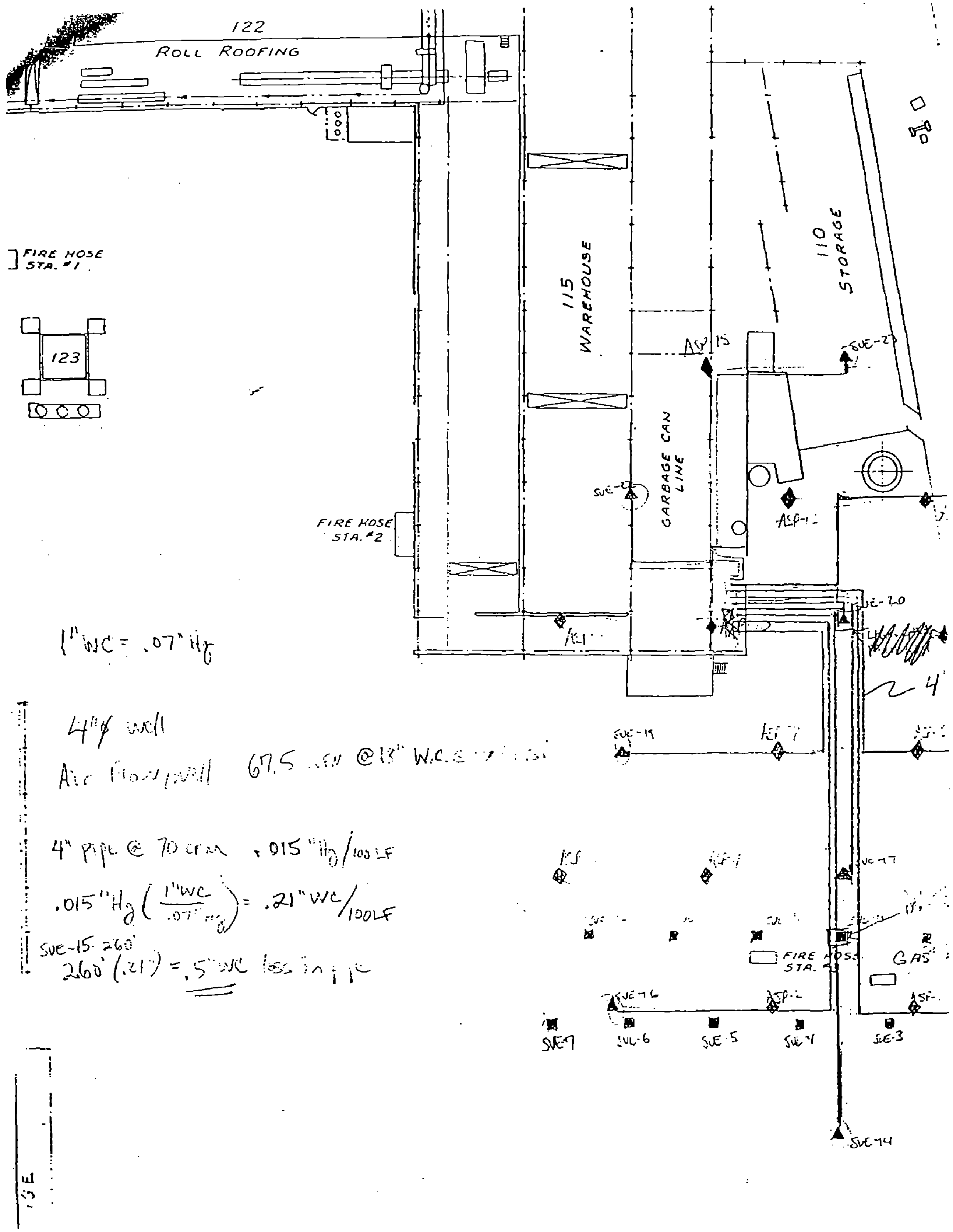
Wheeling-Pittsburgh Steel site in Martins Ferry, Ohio

Air flow rate	= 925 cfm
Influent air temperature	= 55 deg F
Temperature increase across blower	= 50 deg F

Influent vapor phase contaminant concentrations:
Xylene = 19 ppmv

VAPOR PHASE CARBON CONSUMPTION = 10458 lb/year

Most conservative if aliphatics remain at 19 ppmv and adsorb similar to xylene



1" WC = .07" Hg

4"ø well

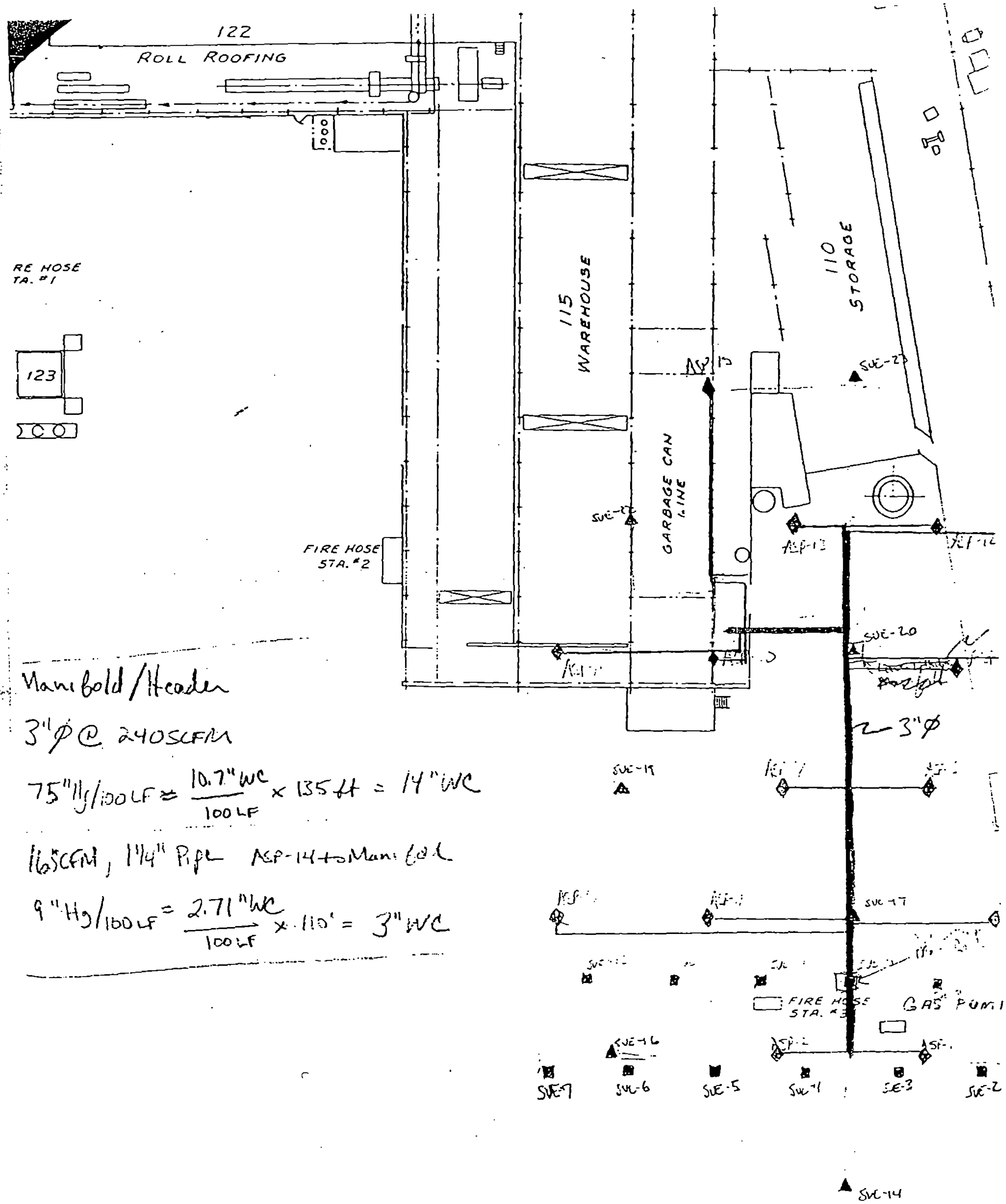
Air flow/well 67.5 cfm @ 18" W.C.

4" pipe @ 70 cfm .015 "Hg/100 LF

$.015\text{"Hg}\left(\frac{1\text{"WC}}{.07\text{"Hg}}\right) = .21\text{"WC}/100\text{LF}$

SVE-15 260'

260' (.21") = .5" WC loss in pipe



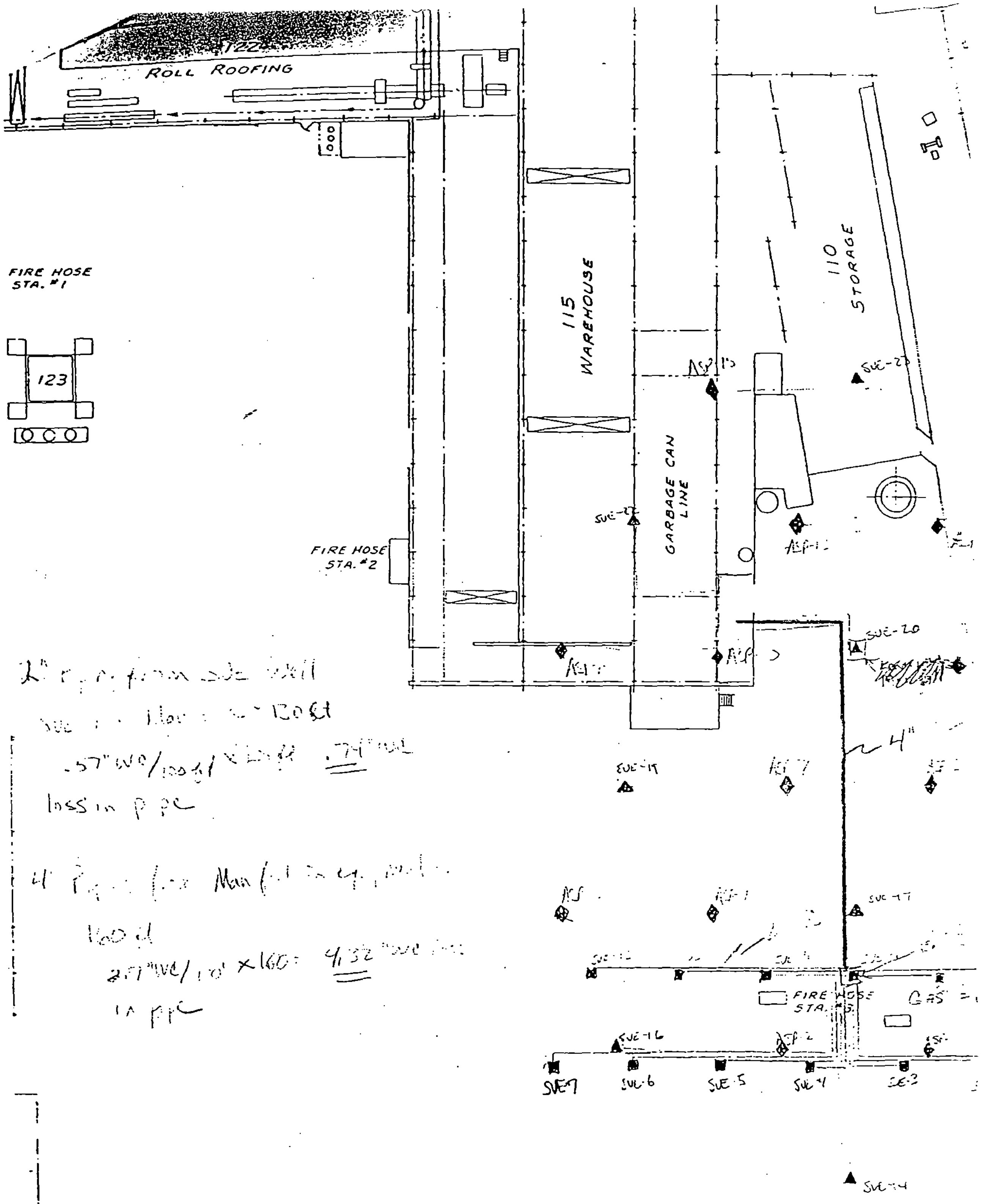
Manifold/Header

3"Ø @ 240SCFM

$75"Hg/100LF \approx \frac{10.7"WC}{100LF} \times 135 ft = 14"WC$

165SCFM, 1¼" Pipe ASP-14 to Manifold

$9"Hg/100LF = \frac{2.71"WC}{100LF} \times 110' = 3"WC$



2" pipe from [illegible] wall

[illegible] 120 cfm

.57" WC/100 ft × [illegible] = .74" WC

loss in pipe

4" pipe from Manifold [illegible]

160 ft

2.7" WC/100' × 160 = 4.32" WC [illegible]

in pipe

VENT-ROI DOCUMENTATION

VENT-ROI Estimate of Effective Radius of Influence

VENT-ROI is a design tool which provides an estimate of the effective cleanup radius (defined as "the maximum distance from a vapor extraction point through which sufficient air is drawn to remove the required fraction of contamination in the desired time") for SVE systems, based on field data readily available from conventional SVE pilot tests. Since 1992, Groundwater Technology, Inc. has been using this model routinely as a design tool for SVE systems.

VENT-ROI assumes that the subsurface is laterally uniform and anisotropic, although the ratio of horizontal-to-vertical permeability may vary. Air infiltration through the ground surface is assumed to be proportional to the subsurface vacuum, which is approximated as dissipating exponentially with distance from the vapor extraction well. Contaminants are assumed to equilibrate between the soil and the gas flowing through the subsurface, with the equilibrium soil gas concentration proportional to soil concentration. Biodegradation is assumed to follow Michaelis-Menten kinetics (zero order at high substrate concentrations, first order at low concentrations) in all areas where oxygen flux to the subsurface significantly exceeds the stoichiometric requirements of the zero order biodegradation rate.

The effective radius, calculated employing these assumptions, is the distance from the vapor extraction well at which subsurface air flow is just sufficient to achieve the remediation goals. It is specific to the desired remediation time, required extent of remediation, and site contaminant. Since air flow is greater between the edge of the contamination plume and a vapor extraction well than it is between two vapor extraction wells, the values for effective radius in these two cases differ and must be calculated separately.

When the effective radius extends to the edge of the contamination plume, as shown in Figure 1, remediation occurs both from the outside of the plume inward (due to lateral introduction of uncontaminated air into the contamination zone) and from the top down (due to vertical infiltration of air). Although the outermost portion of the contamination zone will be treated first, the rate of treatment at this location will be the slowest since the air flux decreases rapidly with distance from the vapor extraction well. A control volume is defined which is a fraction of the contamination zone furthest from the vapor extraction well, i.e. an annulus of outer radius R_E and inner radius ϵR_E. The value for parameter ϵ, typically 0.7 to 0.9, is selected such that vertical infiltration at distances less than ϵR_E from the vapor extraction well provides a rate of remediation roughly comparable to the remediation rate within the control volume due to lateral and vertical introduction of clean air. The control volume is then

$$V_s = \pi(R_E^2 - (\epsilon R_E)^2)h = (1 - \epsilon^2)\pi R_E^2 h \tag{1}$$

and the equation relating the effective radius (R_E) to soil concentration in the control volume (C_s), soil gas recovery rate ($Q°$), and remediation time (t) can be derived as[1]

$$\int_{C_s}^{C_s^\circ} \frac{dC_s}{f(C_s)} = \frac{\int_{r_w}^{R_I}(P_a^2 - P_r^2)r\,dr - \int_{r_w}^{\epsilon R_E}(P_a^2 - P_r^2)r\,dr}{(1-\epsilon^2)\pi R_E^2 \int_{r_w}^{R_I}(P_a^2 - P_r^2)r\,dr}\,\frac{Q^\circ t}{h} \tag{2}$$

where

C_s°	= initial contaminant concentration in the soil
r	= distance from the vapor extraction well
P_a	= absolute atmospheric pressure
P_r	= absolute pressure at distance r from the vapor extraction well
r_w	= radius of vapor extraction well
R_I	= radius of influence

When two or more vapor extraction wells are operated simultaneously, the subsurface air flow between the wells is decreased as the wells compete for air infiltrating from the surface. This reduces the effective radius between wells, as well as the flow per well in response to an applied vacuum. The interwell effective radius, R_{EI}, is the distance from two vapor extraction wells to an equidistant point between them through which just enough air is drawn to remove the required fraction of contamination in the desired time. R_{EI} defines the remediation extent between vapor extraction wells and is always less than R_E, which defines the extent of remediation for a single-well system and for the area external to an array of vapor extraction wells. The equation relating R_{EI} to C_r, Q°, and t is[2]

$$\int_{C_s}^{C_s} \frac{dC_s}{f(C_s)} = \frac{P_a^2 - P_r^2}{2\pi \int_{r_w}^{R_I} (P_a^2 - P_r^2) r\, dr} \frac{Q^\circ t}{h} \tag{3}$$

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Estimation of Effective Cleanup Radius for Soil-Vapor Extraction Systems

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ABSTRACT: Soil-vapor extraction (SVE) is a standard and effective *in situ* treatment for the removal of volatile contaminants from vadose-zone soil. The duration of SVE operation required to reach site closure is quite variable, however, ranging up to several years or more. An understanding of the contaminant recovery rate as a function of distance from each vapor-extraction well allows SVE systems to be designed so that cleanup goals can be achieved within a specified time frame.

A simple one-dimensional model has been developed that provides a rough estimate of the effective cleanup radius (defined as "the maximum distance from a vapor extraction point through which sufficient air is drawn to remove the required fraction of contamination in the desired time") for SVE systems. Because the model uses analytical rather than numerical methods, it has advantages over more sophisticated, multidimensional models, including simplicity, speed, versatility, and robustness.

The contaminant removal rate at a given distance from the vapor-extraction point is assumed to be a function of the local rate of soil-gas flow, the contaminant soil concentration, and the contaminant volatility. Soil-gas flow rate as a function of distance from the vapor-extraction point is estimated from pilot test data by assuming that the infiltration of atmospheric air through the soil surface is related to the vacuum in the soil. Although widely applicable, the model should be used with some caution when the vadose zone is highly stratified or when venting contaminated soil greater than 30 ft below grade. Since 1992, Groundwater Technology, Inc. has been using this model routinely as a design tool for SVE systems.

KEY WORDS: soil-vapor extraction, modeling, design tool, effective radius.

I. BACKGROUND

Soil-vapor extraction (SVE) is a widely used *in situ* remediation technique for treatment of contaminated vadose-zone soil. SVE removes volatile organic compounds (VOCs) from vadose-zone soils by inducing air flow through contaminated

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areas. SVE is typically performed by applying a vacuum to vertical vapor-extraction wells screened through the level of soil contamination, using a vacuum blower. The resulting pressure gradient causes the soil gas to migrate through the soil pores toward the vapor-extraction wells. VOCs are volatilized and transported out of the subsurface by the migrating soil gas. In addition, SVE increases oxygen flow to contaminated areas, thus stimulating natural biodegradation of aerobically degradable contaminants.

The performance of SVE systems improves as the air permeability of the vadose-zone soil increases. SVE is applicable to any compound with a vapor pressure greater than about 1 mmHg. This includes a wide variety of common contaminants such as benzene, toluene, ethylbenzene, xylene, gasoline hydrocarbons, mineral spirits, methyl *t*-butyl ether, tetrachloroethylene, trichloroethylene, 1,1,1-trichloroethane, methanol, acetone, and butanone. Because vapor pressure increases with temperature, SVE also can be applied to semivolatile compounds by heating the vadose zone with steam or hot air.

The efficacy of a SVE system is determined by its ability to draw sufficient air through the contaminated portion of the vadose zone. The number and spacing of vapor-extraction wells and the soil-gas extraction rate are the critical parameters determining air flow through the subsurface. In addition, several modifications to SVE systems are sometimes used in an effort to enhance the flow of air through the contamination zone. These include air injection (forcing air or allowing air to be drawn through wells screened at the level of the vadose-zone contamination) and surface sealing (paving a surface or covering an unpaved surface with a layer of polyethylene film to prevent infiltration of air and water from the surface).

Vapor-extraction well spacing is typically determined by performing a field pilot test to determine the radius-of-influence (ROI) at the site under specified SVE conditions. Historically, pilot test data were interpreted by assessing the distance from the vapor-extraction well where an arbitrary vacuum level (usually 0.01 to 1 in of water column) could be measured in the soil. Although such "rules of thumb" often result in adequate SVE system design, they do not yield any information on the quantity of air moving through the vadose zone. This approach, therefore, cannot provide any assessment of remediation time, nor can it provide design information specific to the contaminant (a system designed to remove benzene will be less effective on the less volatile xylene, for example).

Several alternative approaches to interpretation of SVE pilot test data have recently been developed based on multidimensional modeling of vacuum and soil-gas flow fields in the vadose zone. Johnson *et al.* (1990a, 1990b) derived equations describing air flow in the vadose zone beneath a sealed surface and applied these equations to the SVE remediation of gasoline contaminated soil. Baehr *et al.* (1989) and Marley *et al.* (1990) and others have used numerical solutions for systems with unsealed or partially sealed surfaces, and Lingineni and Dhir (1992) superimposed variable temperature on this approach. Joss and Baehr (1993) have recently adapted MODFLOW, a groundwater numerical modeling program, to SVE applications.

II. MOTIVATION AND OBJECTIVES

The modeling efforts discussed in the previous section represent important advances in the understanding of SVE and provide a basis for more effective design of SVE systems. However, they are not universally applicable. The data available at many small sites where SVE is considered, such as retail gasoline stations and dry cleaning facilities, are often sparse, and budgets rarely exist for gathering the more extensive data required for sophisticated models. Most of these sites have been repeatedly excavated and refilled, creating subsurface anisotropies that confound the limited data. Furthermore, many of the models assume that the surface is sealed, a condition not commonly encountered (and sometimes not even feasible) at such retail sites. Finally, multidimensional models typically require substantial time to input variables and to run, making the design process tedious.

Therefore, the need exists for a model that can provide rapid order-of-magnitude assessments of potential SVE performance based on very limited data. For this application, a simpler one-dimensional model is adequate; the data quality is ordinarily too poor and the subsurface too laden with unidentified anisotropies to warrant a more sophisticated, multidimensional approach. To be most useful, such a model must exhibit the following characteristics:

- Simplicity: cumbersome computer models are intimidating and tend not to be used; a really useful model must be readily accessible by the most junior of engineers.
- Speed: instantaneously, solutions enable an engineer to apply many "what if" scenarios in a short period of time, and hence rapidly converge on an optimum design.
- Versatility: depending on the specific project requirements, the model may be called on to specify SVE well spacing, soil-gas extraction rate, cleanup level, or cleanup time at sites with sealed or unsealed surfaces.
- Robustness: the model must provide reasonable estimates of SVE performance over wide ranges of soil permeability, soil-gas extraction rate, soil temperature, and contaminant volatility.

III. MODEL DERIVATION

The goal of the model is to determine the maximum distance from the vapor-extraction well through which sufficient air is drawn to remove the required fraction of contamination in the desired time. This is the effective radius, R_E, and it differs from the ROI, which is the distance from the vapor-extraction well that vacuum can be detected. The effective radius is based on site-specific conditions and SVE system parameters, and it is specific to the contaminant, cleanup goals, and cleanup time frame.

This derivation is applicable to sites with unsealed surfaces and single-well SVE systems or multiple-well systems in which each well is operated individually, rather than simultaneously (as if often done when surface infiltration of air is insufficient to achieve adequate remediation between vapor-extraction wells). This approach has also been extended to simultaneously operated multiple-well systems and to sites at which an engineered surface seal is to be applied, and these will be the subject of future publications.

Figure 1 illustrates the general air-flow patterns through soil during SVE. Because this derivation is for a single-well SVE system, it is assumed that the effective radius will extend to the edge of the contaminant plume. At the outer edge of the plume, all air entering the contamination zone is initially uncontaminated. As the air flows through the soil, contaminants rapidly equilibrate between soil and air phases (the rapid approach to equilibrium was demonstrated by Johnson *et al.*, 1990a). This equilibration is determined by contaminant-soil concentration, vapor pressure, and water solubility, and by the moisture and organic content of the soil. Of these parameters, only the contaminant soil concentration changes dramatically during the course of the vapor extraction, and so for a given site and contaminant, the equilibrium-gas concentration can be expressed generally as a function of soil concentration:

$$C_g = f(C_s) \tag{1}$$

The rate at which contaminant mass is lost from soil must equal the rate at which the soil gas flowing through the soil carries the contamination away:

$$\frac{dM_s}{dt} = \frac{d(V_s C_s)}{dt} = C_g q = f(C_s)q \tag{2}$$

or

$$\frac{dC_s}{f(C_s)} = \frac{q}{V_s}dt \tag{3}$$

where M_s = mass rate of contaminant removal from soil, t = time, V_s = volume of soil (control volume), q = flow rate of gas through control volume.

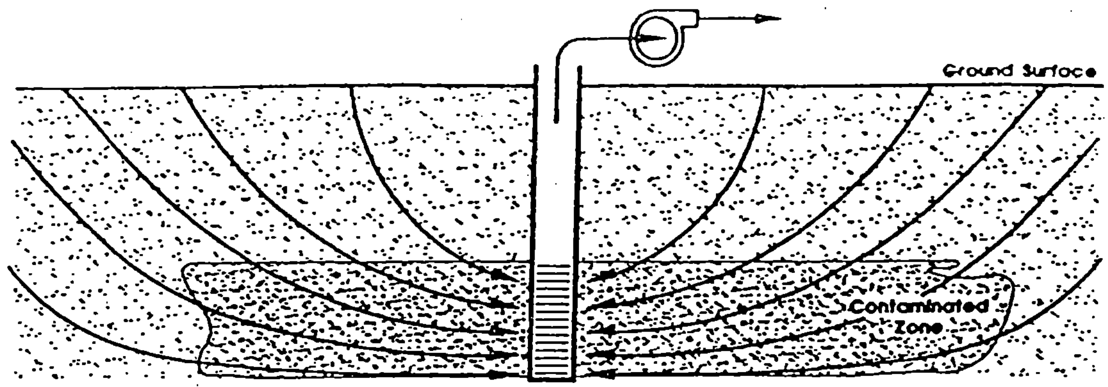

FIGURE 1. Generalized air flow paths in a soil-vapor extraction system.

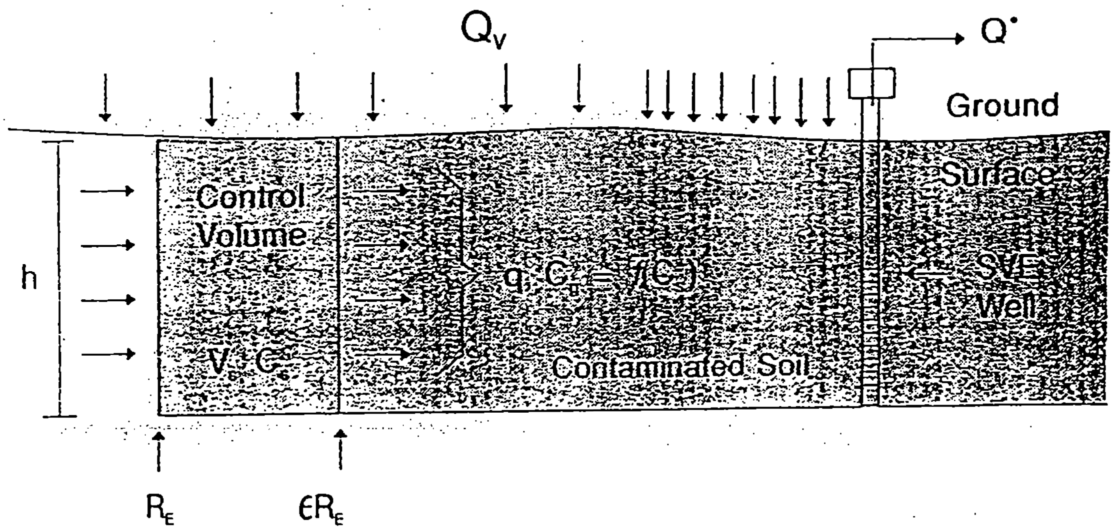

FIGURE 2. Conceptualization of the model. The system is to be designed so that the effective radius, R_E, corresponds to the extent of contamination. Clean air enters the contaminated zone by horizontal movement through the soil and by vertical infiltration through the ground surface. The overall cleanup time is dominated the remediation rate for the contaminated soil between εR_E and R_E ("control volume"), which is determined by the air flow rate, q, through this portion of the contaminated zone.

The contaminated zone is represented as a uniform cylinder of radius R_E and height h, as indicated in Figure 2. Remediation will occur from the outside of the plume inward (due to lateral introduction of uncontaminated air into the contamination zone) and from the top down (due to vertical infiltration of air). Although the outermost portion of the contamination zone will be treated first, the rate of treatment at this location will be the slowest because the air flux decreases rapidly with distance from the vapor-extraction well. The control volume is therefore taken as a fraction of the contamination zone furthest from the vapor-extraction well, that is, an annulus of outer radius R_E and inner radius εR_E, where $0 < \varepsilon < 1$.* The control volume is then

$$V_s = \pi\left(R_E^2 - (\varepsilon R_E)^2\right)h = (1-\varepsilon^2)\pi R_E^2 h \tag{4}$$

The gas flow through the control volume, q, is calculated by assuming that, at a distance r from the vapor-extraction well, any infiltration of atmospheric air through the soil surface is related to the vacuum in the soil and the area of the ground surface:

$$dQ_v = k_v\left(P_a^2 - P_r^2\right)dA = k_v\left(P_a^2 - P_r^2\right)2\pi r\,dr \tag{5}$$

where Q_v = vertical infiltration of atmospheric air, r = distance from the vapor extraction well, P_a = absolute atmospheric pressure, P_r = absolute pressure at distance r from the vapor-extraction well, k_v = constant, A = area of ground surface. The term $k_v(P_a^2 - P_r^2)$ comes from Darcy's Law for flow of a compressible fluid. The constant k_v is related to the permeability of the soil to vertical gas infiltration, as well as to the gas viscosity, density, and travel distance.

Because all the air collected at the vapor-extraction well must come ultimately from the atmosphere through the ground surface, the integral of Equation 5 from the well radius to the radius of influence yields the rate of total soil-gas recovery, Q^o:

$$\int_{r_w}^{R_I} dQ_v = 2\pi k_v \int_{r_w}^{R_I} \left(P_a^2 - P_r^2\right) r\,dr = Q^o \tag{6}$$

where r_w = radius of vapor-extraction well, R_I = radius of influence.

Substituting Equation 6 into Equation 5 and integrating again, this time from the well radius to the inner edge of the control volume, yields

$$\frac{Q_v}{Q^o} = \frac{\int_{r_w}^{\varepsilon R_E} \left(P_a^2 - P_r^2\right) r\,dr}{\int_{r_w}^{R_I} \left(P_a^2 - P_r^2\right) r\,dr} \tag{7}$$

* The value of the parameter ε is selected so that vertical infiltration at distances less than εR_E from the vapor-extraction well provides a rate of remediation at least comparable with the remediation rate within the control volume due to lateral and vertical introduction of clean air. In other words, by the time the control volume is clean, the rest of the contaminated zone will have been remediated as well. For most sites where SVE is considered, ε ranges from 0.7 to 0.9. Within this range, the precise value of ε selected is not crucial, because values of R_E computed from the design equation derived later are not particularly sensitive to changes in ε, varying typically by 10% or less.

The gas passing through the control volume is the total gas flow collected less the vertical infiltration that occurs closer to the SVE well

$$q = Q_v^o - Q_v = Q_v^o \frac{\int_{r_w}^{R_I} \left(P_a^2 - P_r^2\right) r\, dr - \int_{r_w}^{\varepsilon R_E} \left(P_a^2 - P_r^2\right) r\, dr}{\int_{r_w}^{R_I} \left(P_a^2 - P_r^2\right) r\, dr} \tag{8}$$

Combining Equations 3, 4, and 8 and integrating yields

$$\int_{C_s}^{C_s^o} \frac{dC_s}{f(C_s)} = \frac{\int_{r_w}^{R_I} \left(P_a^2 - P_r^2\right) r\, dr - \int_{r_w}^{\varepsilon R_E} \left(P_a^2 - P_r^2\right) r\, dr}{\left(1-\varepsilon^2\right)\pi R_E^2 \int_{r_w}^{R_I} \left(P_a^2 - P_r^2\right) r\, dr} \frac{Q^o t}{h} \tag{9}$$

where C_s^o = initial contaminant concentration in the soil.

Whenever $dC_s/f(C_s)$ and $P_r^2 r\, dr$ are analytically integrable, Equation 9 provides a vehicle for relating the effective radius (R_E) to soil concentration in the control volume (C_s), soil-gas recovery rate (Q^o), and remediation time (t) without the use of cumbersome numerical methods. Depending on site-specific conditions, any of a number of expressions for P_r and $f(C_s)$ are appropriate.

For example, Johnson *et al.* (1990a) derived the following expression for P_r, which is applicable when the ground surface is sealed:

$$P_r^2 = P_w^2 + \left(P_a^2 - P_w^2\right) \frac{\ln\left(r / r_w\right)}{\ln\left(R_I / r_w\right)} \tag{10}$$

where P_w = absolute pressure in the vapor extraction well.

When the ground surface is not sealed, P_r can be approximated by the following simple exponential relationship over a substantial range of distances from the vapor-extraction well (i.e., when r is greater than a few feet) (Mohr, personal communication, 1992):

$$\ln\left(P_r\right) = c_1 r + c_2 \tag{11}$$

where c_1 and c_2 are fitted constants.

At lower soil concentrations, it is proper to assume ideal partitioning between soil and gas ($f(C_s) = K_{gs} C_s$), whereas above a compound-specific threshold soil concentration, vapor concentration becomes independent of soil concentration

(Lyman *et al.*, 1990); under such conditions, $f(C_s)$ is simply the contaminant saturated-vapor density and is constant. More complex representations of $f(C_s)$ are required for soil contaminated with a diverse mixture of compounds, such as gasoline. As SVE proceeds, the more volatile species are preferentially removed and the remaining contamination becomes less volatile. Therefore, $f(C_s)$ must decrease as C_s decreases, and this effect is demonstrated in Figure 3 for fresh and weathered gasoline. As is evident from the figure, the decrease in $f(C_s)$ with decreasing C_s is roughly exponential.

IV. MODEL IMPLEMENTATION AND LIMITATIONS

Equation 9 contains the following parameters:

- gas-soil equilibrium relationship ($f(C_s)$), which is a function of soil-gas temperature and contaminant volatility
- pressure as a function of distance from the vapor-extraction well (P_r), which is a function of vapor-extraction well pressure (P_w) if Equation 10 is used the fitted constants c_1 and c_2 if Equation 11 is used
- depth of vented interval (h)†
- soil-gas recovery rate (Q^o)
- treatment time (t)
- effective radius (R_E)
- vapor-extraction well radius (r_w)
- radius of influence (R_I) and
- extent of remediation ($1 - C_s/C_s^o$).

Equation 9 can be evaluated to solve for any of these variables, provided all others are specified. The model has been implemented in a computer program written in Basic that prompts the user to choose which variable to solve for (effective radius, cleanup time, extent of remediation, or soil-gas recovery rate). The user then

† The vented interval is the portion of the vadose zone through which air movement is induced during SVE. If the vadose zone is fairly homogeneous, air movement will be induced throughout, and it is appropriate to consider the vented interval to be the depth to the bottom of the vapor-extraction well. When the vadose zone is stratified, each contaminated stratum is vented separately. If a contaminated low permeability stratum underlying a clean higher permeability stratum is being vented, the vented interval should be considered to be the thickness of the low permeability stratum. This approach is not applicable, however, for a higher permeability stratum underlying a substantial, continuous lower permeability stratum.

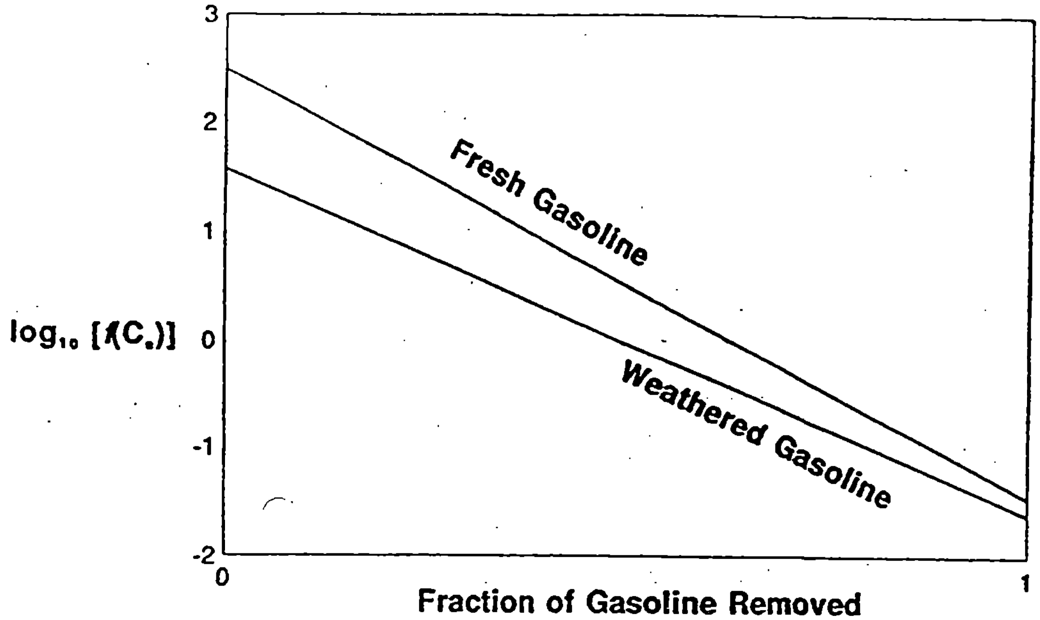

FIGURE 3. $f(C_s)$ for fresh and weathered gasoline. This figure is derived from constituent data in Johnson *et al.* (1990a).

specifies the contaminant, choosing from a list of common volatile soil contaminants or entering a new contaminant with its vapor pressure and vaporization enthalpy. Values for all other parameters are then entered, and the value of the dependent variable is displayed virtually instantaneously.

Of course, the simplifying assumptions that provide this ease of calculation also contribute to the uncertainty in the result. Significant subsurface anisotropies (sewers, foundations, etc.) can upset the assumed radial symmetry of the air flow, and extreme stratification can make the assumption of uniform air flow across the vented stratum inappropriate. However, site data are often inadequate to characterize the anisotropies in any event, and it is rare that horizontal and vertical permeabilities differ by more than an order of magnitude within a vented stratum. Equation 9 can therefore provide reasonable rough estimates of SVE system performance over a wide range of site conditions.

However, because the model assumes the vadose-zone conditions to be uniform with depth, caution should be exercised when applying this model to SVE systems venting strata greater than about 30 ft below grade. In addition, Equation 9 is not appropriate when vertical infiltration of air through the ground surface is virtually nonexistent. Such a situation would arise during venting of a high permeability stratum underlying an extensive, substantial, and continuous stratum of much lower permeability. Fortunately, such situations occur only rarely, and they can be modeled effectively using the sealed surface approach taken by Johnson *et al.* (1990a, 1990b).

V. EXAMPLES

Equation 9 indicates that for a fixed cleanup level, changes in vapor extraction rate (Q^o), cleanup time (t), and depth of the vented interval (h) will not effect the effective radius so long as $Q^o t/h$ remains constant. In other words, the same system performance can be obtained in half the time by doubling the vapor-extraction rate or halving the depth of the vented interval.

Figure 4 shows an example of how effective radius varies with $Q^o t/h$ for a variety of common volatile soil contaminants (where cleanup is defined as 90% removal, ideal soil-vapor partitioning and an unsealed surface are assumed). The conditions in this example are typical for SVE systems, and the resulting effective radius varies from a few feet to as much as 70 ft. Effective radius is most sensitive to the volatility of the contaminant; the effective radius for weathered gasoline is 3 to 10 times less than for 1,1,1-trichloroethane under the same conditions. Large changes in $Q^o t/h$ are required to substantially affect effective radius, especially for the more volatile contaminants; doubling the effective radius generally requires increasing $Q^o t/h$ by a factor of 10 to 50.

This relationship between effective radius and $Q^o t/h$ has profound implications regarding SVE system design. Decreasing the spacing between vapor-extraction wells increases the number of wells required, but also decreases the effective radius required. This greatly reduces remediation time and/or soil-gas recovery rate requirements. For example, a reduction in effective radius from 40 ft to 30 ft would

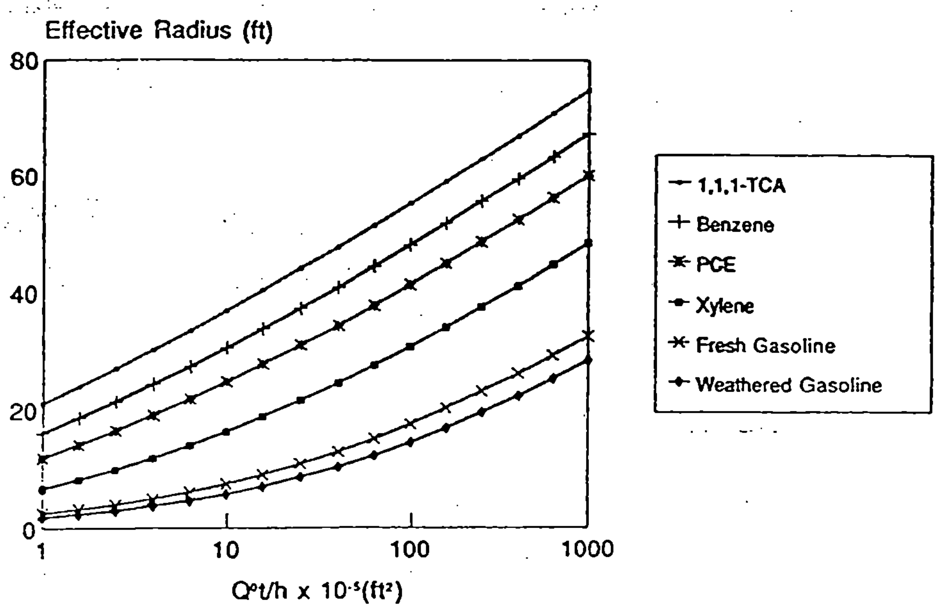

FIGURE 4. Effective radius at a typical SVE site as a function of $Q^o t/h$ for several volatile contaminants (90% cleanup, ideal soil-vapor partitioning, and unsealed surface assumed).

nearly double the number of vapor-extraction wells but would also reduce remediation time by nearly an order of magnitude. The lower soil-gas recovery rates required when effective radius is reduced in many cases results in lower costs associated with less powerful blowers that more than make up for the costs associated with additional vapor-extraction wells.

Effective radius also varies with desired cleanup level, as shown in Figure 5 for a typical unsealed system where Q^o is 30 scfm per vapor extraction well, h is 10 ft, and t is 1 year. Contaminant volatility has a large impact on effective radius, but increasing cleanup level from 90% to 99.99% only decreases the effective radius for single component systems by 35 to 50%. For contaminant mixtures such as gasoline, however, changing cleanup level can have a more dramatic effect. This is because the volatility of the mixture decreases over the course of the SVE process, because the most volatile components are removed first. The volatility of contaminant mixtures is thus a function of cleanup level, and so effective radius is strongly affected by changes in cleanup level.

This model can also be used to assess the effect of soil temperature on effective radius, cleanup level, or remediation time. The effectiveness of SVE can be significantly enhanced by injecting hot air, steam, or radio frequency to heat vadose-zone soil, because $f(C_s)$ increases rapidly with increasing temperature. Evaluating Equation 9 at various temperatures gives an indication of the magnitude of SVE enhancement. For example, 90% removal of fresh gasoline from a 10-ft depth of medium sand, 20 ft from a vapor-extraction well pulling 30 cfm is

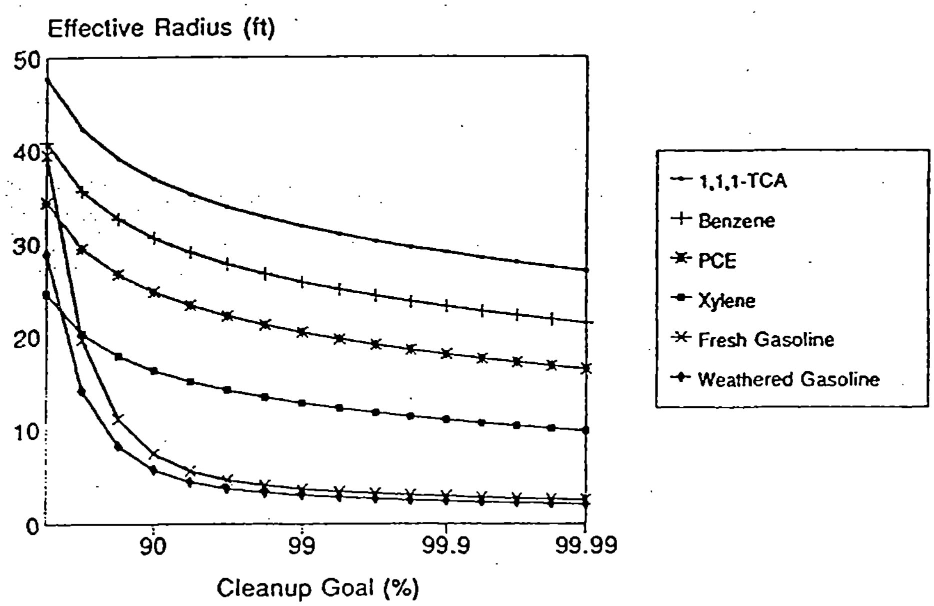

FIGURE 5. Effective radius at a typical SVE site as a function of cleanup goal (Q^ot/h = 1.6 × 10^6 ft^2; ideal soil-vapor partitioning and unsealed surface assumed).

estimated to require almost 5 years of SVE operation at 50°F, but 16 months at 100°F, 6 months at 150°F, and 10 weeks at 200°F.

VI. CONCLUSIONS

A simple one-dimensional model has been developed that can provide rapid order-of-magnitude assessments of potential SVE performance based on very limited data. Because the model uses analytical rather than numerical methods, it has advantages over more sophisticated, multidimensional models, including simplicity, speed, versatility, and robustness. Although accuracy and resolution are somewhat reduced, the use of this model instead of more complicated approaches is generally justified, given the limited site characterization data ordinarily available and the subsurface anisotropies commonly encountered at most small SVE sites. Since 1992, Groundwater Technology, Inc. has been using this model routinely as a design tool for SVE systems.

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SCALING UP SINGLE-WELL VAPOR EXTRACTION PILOT TESTS TO MULTIPLE-WELL SYSTEMS

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ABSTRACT

Soil vapor extraction is a common remediation technology for *in situ* treatment of vadose zone soil containing volatile or aerobically degradable contaminants. Pilot tests are routinely performed to assess the applicability of this technology and to size components for full scale remediation systems. Tests are typically performed on a single well, however the final system design generally involves multiple wells. Wells compete for air in a multiple-well system, and so the total air recovered is rarely proportional to the number of vapor extraction wells. Significant errors in well spacing and component sizing can occur when this effect is not taken into account.

A design tool has been developed which estimates the performance of multiple-well soil vapor extraction systems based on a single-well pilot test. Air flow in a single-well system originates from air infiltration over the entire site surface; a smaller area for surface infiltration is available to each well in multiple-well systems, since the capture zone for each vapor extraction well is bounded by the capture zones for adjacent wells. The driving force for surface infiltration is the subsurface vacuum field, which is measured during the pilot test. The product of the surface area between the wells and the air flux resulting from this driving force yields an estimate of the total air flow rate between wells. This facilitates more accurate estimates of blower sizing, offgas treatment selection, and well spacing requirements.

The predictions of this design tool are compared to the performance of 13 operating multiple-well soil vapor extraction systems. In general, the observed and predicted results agree, although substantial scatter is observed in the data.

BACKGROUND

Soil vapor extraction (SVE) is a widely used *in situ* remediation technique for treatment of contaminated vadose zone soil. SVE removes volatile organic compounds (VOCs) from vadose zone soils by inducing air flow through contaminated areas. SVE is often performed by applying a vacuum, using a vacuum blower, to a line or array of vertical vapor extraction wells. The resulting pressure gradient causes the soil gas to migrate through the soil pores toward the vapor extraction wells. VOCs are volatilized and transported out of the subsurface by the migrating soil gas. In addition, SVE increases oxygen flow to contaminated areas, stimulating natural biodegradation of aerobically degradable contaminants. In practice, SVE is applicable to any compound which is aerobically biodegradable or which has a vapor pressure greater than about 1 mm Hg. This includes a wide variety of common contaminants, such as many petroleum hydrocarbons, chlorinated VOCs, and oxygen-containing solvents. Since vapor pressure increases with temperature, SVE also can be applied to semi-volatile compounds by heating the vadose zone with steam or hot air.

The efficacy of a SVE system is determined by its ability to draw sufficient air through the contaminated portion of the vadose zone to meet the remediation objectives within the required time frame. Pilot tests are routinely performed to determine well spacing and to size components for full scale SVE systems, based on the attainable soil gas recovery rate and the attenuation of soil vacuum with distance from the vapor extraction well. Tests are typically performed on individual, often pre-existing vertical wells; however the final system design generally involves multiple wells. Wells compete for air in a multiple-well system, and so the total air recovered is rarely proportional to the number of vapor extraction wells.

Accurate selection of well spacing, vapor extraction blowers, and offgas treatment technology requires reliable prediction of the vacuum/flow response of the SVE system. Significant errors in well spacing and component sizing can occur when this effect is not taken into account. Therefore, a design tool relating the performance of single-well pilot tests to full scale multiple-well SVE systems is required.

MOTIVATION AND OBJECTIVES

One approach to predicting changes in flow/vacuum performance of SVE systems as a function of system geometry and orientation is the use of multi-dimensional modeling of vacuum and soil gas flow fields in the vadose zone. Baehr, Marley, and others have employed such numerical solutions for systems with unsealed or partially sealed surfaces,[1,2] and Lingineni and Dhir superimposed variable temperature on this approach.[3] Joss and

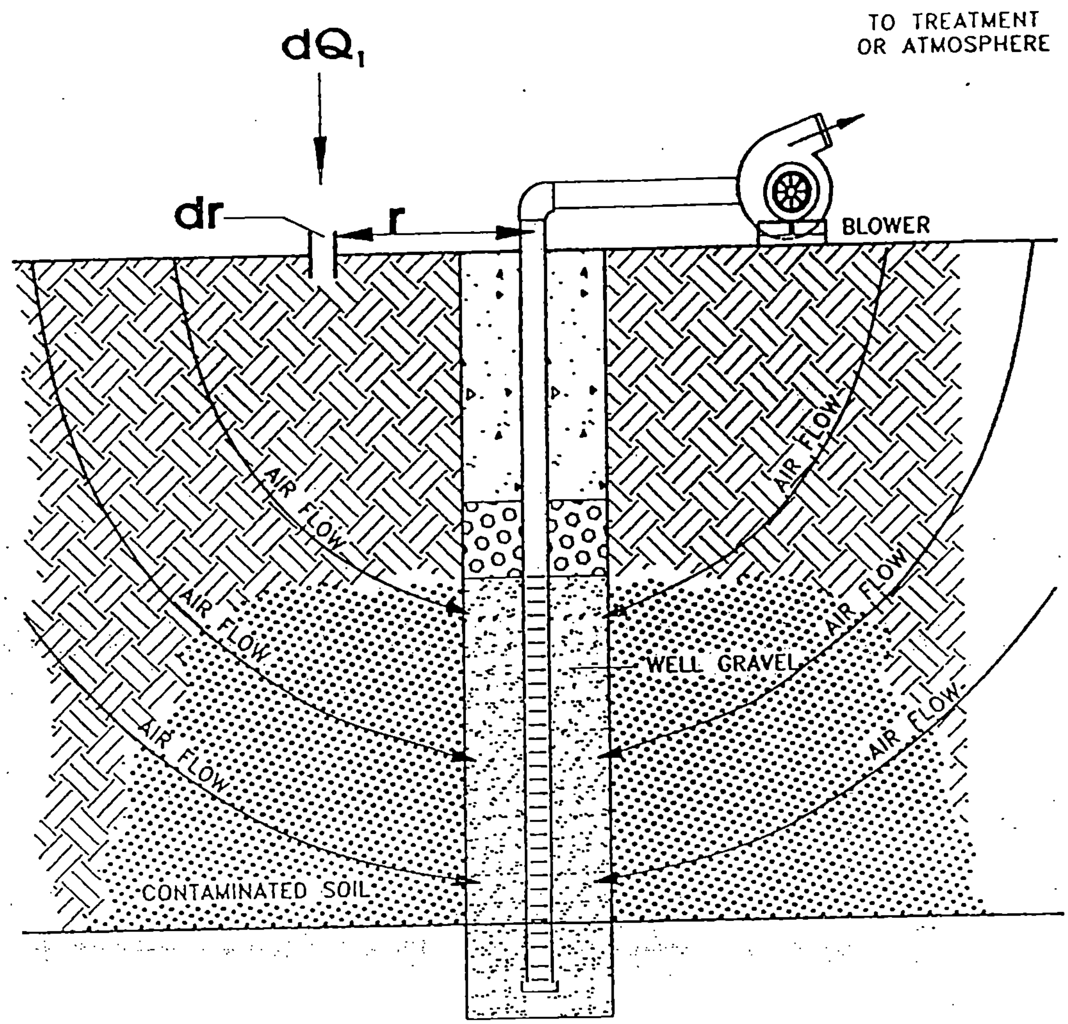

Figure 1
Typical soil vapor extraction well with generalized air flow lines. The driving force for air infiltration is the difference between the squares of the subsurface and atmospheric pressures. At any distance **r** from the vapor extraction well, this driving force acts to produce a differential flow, dQ_1, through an area of ground surface represented by an annulus of differential thickness, **dr.**

Baehr have recently adapted MODFLOW, a groundwater numerical modeling program, to SVE applications.[4]

It is not always feasible to apply these sophisticated models, however. The data available at many small sites where SVE is considered, such as retail gasoline stations and dry cleaning facilities, are often sparse, and budgets rarely exist for gathering the more extensive data required for multi-dimensional models. Most of these sites have been repeatedly excavated and refilled, creating subsurface anisotropies which confound the limited data. Multi-dimensional models typically require substantial time and training to input variables and to run, making the design process tedious and costly.

Therefore, the need exists for a design tool which can provide rapid order-of-magnitude assessments of flow/vacuum performance of SVE systems, based on the limited data typically obtained from a routine SVE pilot study. To be most useful, such a design tool must exhibit the following characteristics:

- **simplicity** - cumbersome computer models are intimidating and tend not to be used; a really useful design tool must be readily accessible by the most junior of engineers.

- **speed** - instantaneous solutions enable an engineer to apply many "what if" scenarios in a short period of time, and hence rapidly converge on an optimum design.

- **versatility** - depending on the specific project requirements, the design tool may be called upon to predict performance of prospective SVE systems with varying numbers of wells and patterns of well placement.

- **robustness** - the design tool must provide reasonable estimates of vacuum/flow response over wide ranges of system geometry, applied vacuum, soil gas extraction rate, and soil permeability.

DESIGN TOOL DEVELOPMENT

The vacuum/flow response for a vapor extraction system is a function of the number, spacing, and well placement pattern, as well as soil and other site-specific characteristics. The approach to modeling flow in multiple-well systems developed below is specific to two common placement patterns, straight lines and hexagonal arrays. The approach can be readily extended to any conceivable well placement pattern, however. Relating multiple-well flow to pilot study results involves comparing the equations for the multiple-well system with the comparable equation derived for single-well flow.

Flow Response of a Single Well

When a vacuum is applied to a vapor extraction well, air flow is induced through the surrounding soil. The ultimate source of the air is the infiltration of atmospheric air through the ground surface, as shown in Figure 1. The driving force for this air infiltration is the difference between the squares of the subsurface and atmospheric pressures.[2,5]. At any distance r from the vapor extraction well, this driving force acts through an area of ground surface represented by an annulus of differential thickness, i.e. $2\pi r dr$. Therefore, the total flow extracted by a single well is

$$Q_1 = \int dQ_1 = 2\pi k \int_{r_w}^{R_I} (P_r^2 - P_a^2) r dr \qquad (1)$$

where
Q_1 = flow from a single well
r_w = well radius
R_I = radius of vacuum influence
k = soil conductance to air flow
P_r = subsurface pressure
P_a = atmospheric pressure

The subsurface pressure as a function of distance from the vapor extraction well, P_r, is routinely determined from reduction of pilot test data. The radius of influence may be fixed at a finite value or may be considered infinite, depending on site-specific physical constraints and the data reduction approach used for determining P_r. The conductance, k, is a function of soil permeability, air viscosity, and atmospheric pressure and is not routinely quantified from pilot test data. Doing so is not necessary, however, since this parameter will be canceled out in subsequent analyses.

Flow Response of Two-well and Linear Systems

If two identical vertical vapor extraction wells, spaced a distance of 2R apart, are installed in a homogeneous medium and a constant vacuum is applied to both, the air flow recovered by the two wells will not be simply twice the air flow for a single well. This is because the wells will compete for air infiltrating the ground surface between the two wells.

To model this effect, assume that air infiltrating the ground surface migrates to the vapor extraction well nearest the point of infiltration. The capture zone for each well is therefore bounded by a line which represents the locus of points equidistant from the two wells, as shown in Figure 2. As shown on the right side of Figure 2, infiltration will be the same for each well as for the single-well system so long as $r \leq R$. When $r > R$, the area available for surface infiltration is reduced by the fraction Θ_r / π, where $\Theta_r = \arcsin(R/r)$, as indicated by the left side of Figure 2. Thus, the total air collected by each well is

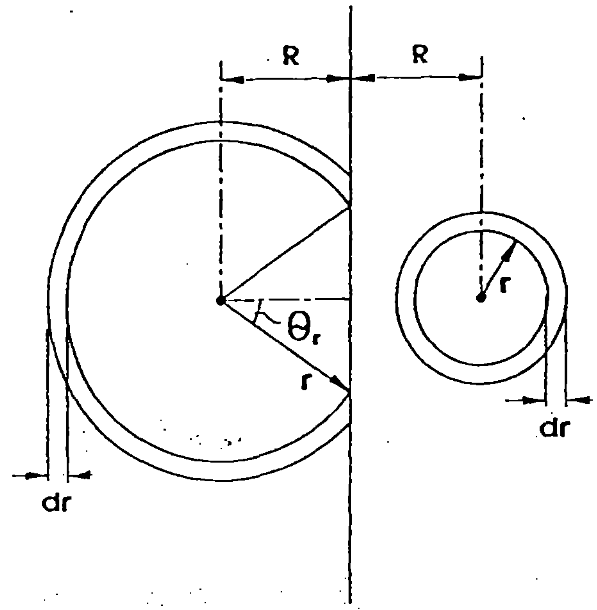

Figure 2
Modeling competition for air infiltrating the ground surface between two vapor extraction wells (•) with spacing 2R. The capture zone for each well is bounded by the locus of points equidistant from the two wells. When $r \leq R$, infiltration will be the same for each well as for the single-well system; when $r > R$, the area available for surface infiltration is reduced by the fraction Θ_r/π.

$$Q_2 = 2\pi k \int_{r_w}^{R} (P_r^2 - P_a^2) r dr + 2\pi k \int_{R}^{R_I} (P_r^2 - P_a^2)(1 - \frac{\Theta_r}{\pi}) r dr \qquad (2)$$

where Q_2 = flow per well from a two-well system

The relative flow per well for a two-well system and single-well system, assuming identical well construction and applied vacuum, is found by dividing equation (2) by equation (1):

$$\frac{Q_2}{Q_1} = \frac{\int_{r_w}^{R} (P_r^2 - P_a^2) r dr + \int_{R}^{R_I} (P_r^2 - P_a^2)(1 - \frac{\Theta_r}{\pi}) r dr}{\int_{r_w}^{R_I} (P_r^2 - P_a^2) r dr} \qquad (3)$$

Note that this expression does not contain the conductance term, which means that scaling up from a single-well pilot test to a two-well SVE system does not require calculation of soil permeability.

Extending this analysis to a straight line of n vapor extraction wells spaced 2R feet apart results in a more general expression than equation (3):

$$\frac{Q_{n,line}}{Q_1} = \frac{\int_{r_w}^{R}(P_r^2-P_a^2)rdr + \int_{R}^{R_I}(P_r^2-P_a^2)(1-\frac{(2n-2)\theta_r}{n\pi})rdr}{\int_{r_w}^{R_I}(P_r^2-P_a^2)rdr} \quad (4)$$

where $Q_{n,line}$ = flow per well from a system of n vapor extraction wells in a straight line

Flow Response of Multiple-well, Hexagonal Array Systems

In SVE systems with three or more vapor extraction wells, the wells are usually placed so that the lines connecting the well form approximately equilateral triangles, as shown in Figure 3. In this case, the capture zone for each well is bounded two to six lines representing the locus of points equidistant from each pair of adjacent wells. These lines intersect at 120° angles (Figure 3), and when sufficient wells are present, form an array of regular hexagons (Figure 4).

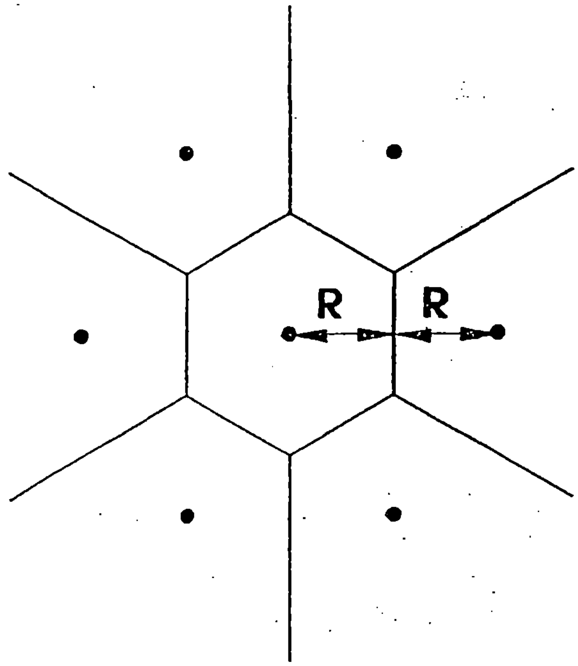

Figure 4
A Hexagonal Array of Seven Vapor Extraction Wells

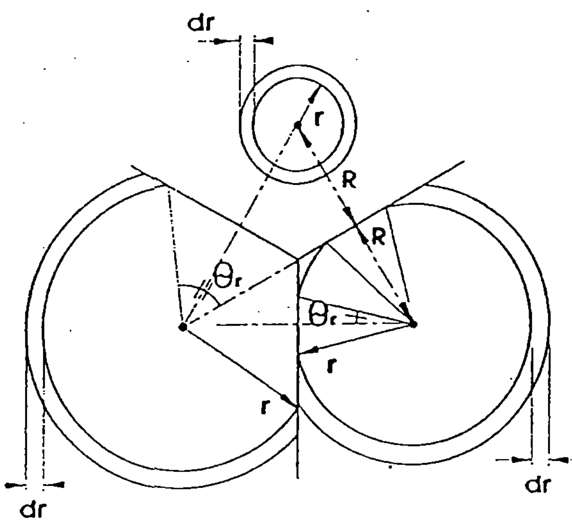

Figure 3
Modeling competition for air infiltrating the ground surface between three vapor extraction wells (•), placed in an equilateral triangle with spacing 2R. The capture zone for each well is bounded by the locus of points equidistant from each pair of adjacent wells. When $r \le R$, infiltration will be the same for each well as for the single-well system; when $R < r < 2R/\sqrt{3}$, the area available for surface infiltration is reduced by the fraction $2\theta_r/\pi$ (lower right); when $r \ge 2R/\sqrt{3}$, surface infiltration is reduced by the fraction $1/6 + \theta_r/\pi$ (lower left).

To model the system depicted in Figure 3 which has three wells spaced a distance of 2R apart, assume again that air infiltrating the ground surface migrates to the vapor extraction well nearest the point of infiltration. As shown at the top of Figure 3, infiltration will be the same for each well as for the single-well system, so long as $r \le R$. When $R < r < 2R/\sqrt{3}$, the area available for surface infiltration is reduced by the fraction $2\theta_r/\pi$, as depicted in the lower right of Figure 3. The lower left of Figure 3 shows that when $r \ge 2R/\sqrt{3}$, the area available for surface infiltration is reduced by the fraction $1/6 + \theta_r/\pi$. The relative flow per well for a three-well and single-well system, assuming identical well construction and applied vacuum, is then:

$$\frac{Q_{3,array}}{Q_1} = \frac{\int_{r_w}^{R}(P_r^2-P_a^2)rdr}{\int_{r_w}^{R_I}(P_r^2-P_a^2)rdr} + \frac{\int_{R}^{2R/\sqrt{3}}(P_r^2-P_a^2)(1-\frac{2\theta_r}{\pi})rdr}{\int_{r_w}^{R_I}(P_r^2-P_a^2)rdr} + \frac{\int_{2R/\sqrt{3}}^{R_I}(P_r^2-P_a^2)(\frac{5}{6}-\frac{\theta_r}{\pi})rdr}{\int_{r_w}^{R_I}(P_r^2-P_a^2)rdr} \quad (5)$$

where $Q_{3,array}$ = flow per well from a three-well triangular system

Extending this analysis to a hexagonal array of n vapor extraction wells spaced 2R feet apart requires classification of vapor extraction wells as either interior or exterior. Interior wells are adjacent to six other wells, exterior wells are adjacent to fewer than six (the seven-well array in Figure 4 has one interior and six exterior vapor extraction wells). The distinction is important because interior wells are assumed to have no influence beyond a distance of $2R/\sqrt{3}$. The general expression for the relative flow per well for a hexagonal array of n wells and a single-well system is:

$$\frac{Q_{n,Array}}{Q_1}=\frac{\int_{r_w}^{R}(P_r^2-P_a^2)\,r\,dr}{\int_{r_w}^{R_1}(P_r^2-P_a^2)\,r\,dr}+\frac{\int_{R}^{2R/\sqrt{3}}(P_r^2-P_a^2)\left(1-\frac{(6n-2n_e-6)\theta_r}{n\pi}\right)r\,dr}{\int_{r_w}^{R_1}(P_r^2-P_a^2)\,r\,dr}$$

$$+\frac{\frac{n_e}{n}\int_{2R/\sqrt{3}}^{R_1}(P_r^2-P_a^2)\left(\frac{n_e+2}{2n_e}-\frac{\theta_r}{\pi}\right)r\,dr}{\int_{r_w}^{R_1}(P_r^2-P_a^2)\,r\,dr} \qquad (6)$$

where $Q_{n,Array}$ = flow per well from an n-well hexagonal array of vapor extraction wells
n_e = number of exterior vapor extraction wells

As evidenced by equations (3) through (6), flow per well under conditions of constant vacuum and well geometry is a function of

- the number of vapor extraction wells;
- the spacing of vapor extraction wells; and
- the variation of vacuum dissipation with distance from the vapor extraction wells.

Figure 5 shows how air flow varies with well spacing for the seven-well system depicted in Figure 4. The two curves shown represent significant vacuum dissipation with distance from the vapor extraction well (a condition reflective of low soil permeability and/or isotropic flow) and a slower decrease with distance from the vapor extraction well (a condition reflective of highly permeable soils and/or a strong preference for horizontal air flow within the subsurface). In both cases, flow per well approaches the obvious limit of 1/7 the single-well value as well spacing approaches zero. In the case of significant vacuum dissipation, flow per well approaches the single-well value asymptotically as well spacing is increased. At lower vacuum dissipation, flow per well is substantially reduced even at relatively large distances from the vapor extraction well. Under such circumstances, interwell subsurface flow may be so reduced that conventional SVE design is not capable of timely site remediation. Alternative approaches, such as air injection or horizontal SVE may be required.

LIMITATIONS

While the above discussion provides the basis for a useful design tool, it is not applicable to all SVE situations without qualification. The simplifying assumptions which provide the ease of calculation also contribute to the uncertainty in the result. For example, the actual resistance to air flow provided by the soil matrix may be non-uniform due to subsurface anisotropies and anthropogenic structures (sewers, foundations, etc.). Unfortunately, site data are often inadequate to characterize fully such features. This design tool may be useful as a basis for design, but SVE installations must be executed with sufficient flexibility to enable compensation for such unidentified features.

This approach is somewhat conservative in that it assumes each vapor extraction will have no vacuum influence beyond its capture zone. This is ordinarily a reasonable assumption; since vacuum decreases exponentially with distance from the vapor extraction well, the vacuum at any point will be dominated by the influence of the nearest vapor extraction well. However, contributions to subsurface vacuum from more distant vapor extraction wells would be expected to be more significant when the wells are closely spaced.

Flow response to an applied vacuum is occasionally observed to increase somewhat with time, especially when fine grained soils are vented. This change usually occurs over weeks or months of operation; the duration of most SVE pilot tests is only a few hours or days, so such an increase in flow would not be anticipated by this design tool. SVE system designs in tight soils should therefore take into account the possibility of a gradual change in vacuum/flow response.

In some SVE applications, an engineered surface seal is placed over the area to be vented and/or air is injected into the subsurface. The design tool described above is not applicable in these cases.

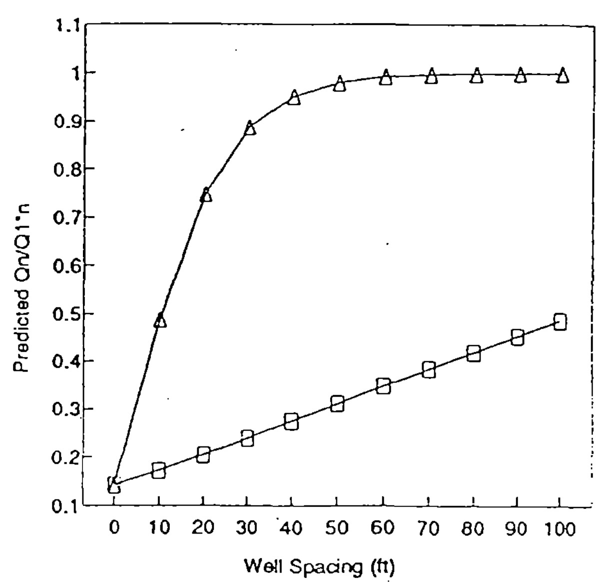

Figure 5
Ratio of system flow per well to single well flow for the seven-well array depicted in Figure 4, as a function of well spacing. Predictions are based on equation (6).
-Δ- = high vacuum dissipation with distance
-□- = low vacuum dissipation with distance

Table 1

Observed and Predicted Vacuum/Flow Response for Selected Operating SVE Sites in Massachusetts and Connecticut

Site No.	No. of Wells	Well Spacing (ft)	Well Placement Pattern	Vacuum Dissipation[a]	System Flow (cfm)	System Flow / (Single Well Flow)*n		Relative Percent Difference[b]
						Observed	Predicted	
1	2	50	Linear	moderate	78	1.08	0.88	20.5
2	2	64	Linear	low	124	1.23	0.90	31.5
3	2	50	Linear	moderate	125	1.19	0.92	25.4
4	3	16	Array	low	66	0.69	0.47	36.9
5	3	76	Array	moderate	180	1.28	0.93	31.4
6	5	54	Array	low	434	0.96	0.65	38.8
7	5	50	Array	moderate	275	0.48	0.83	-52.8
8	6	58	Array	low	200	0.69	0.58	13.4
9	7	56	Array	high	220	0.83	0.98	-16.7
10	7	12	Array	very low	200	0.18	0.19	1.3
11	7	54	Array	very high	180	0.54	1.00	-60.1
12	8	42	Array	high	200	0.76	0.86	-12.3
13	9	20	Linear	very low	230	0.35	0.21	48.4

[a]Qualitative description of the extent to which subsurface vacuum is attenuated with distance from the vapor extraction well
[b]The relative percent difference for two values, a and b, is defined as (2)(100%)(a-b)/(a+b)

EXAMPLES

Table 1 summarizes the vacuum/flow response of 13 multiple-well SVE systems, operating in Massachusetts and Connecticut, relative to that observed in a single-well pilot test. The number of wells in the multiple-well systems ranges from 2 to 9, well spacing from 12 to 76 feet, total flow from 66 to 434 cfm, and vacuum dissipation in the subsurface from very low to high. Both linear and two-dimensional well placement patterns are represented. The flow per well for the multiple-well system is divided by flow from the single-well pilot test, corrected for any differences in applied vacuum or well construction, as described in a separate publication.[6] This ratio is compared with the values predicted using equations (3) through (6). Observed ratios are plotted against predicted values in Figure 6.

Perfect agreement of observed and predicted values would produce a line of slope 1 passing through the origin, as shown in Figure 6, with a correlation coefficient of 1. Linear regression of the actual data yields a slope of 0.93 and a y-intercept of 0.13, close to the theoretical parameters. The observed and predicted flows therefore generally agree, however, there is substantial scatter in the data as reflected by the correlation coefficient of 0.73. The absolute value of the relative percent difference between the observed and predicted values range from 1% to 53%, with an average of 29%. A number of sources of error may be contributing to the uncertainty, including:

- subsurface anisotropies, which will result in different vacuum/flow responses for different vapor extraction wells;
- differences in construction of vapor extraction wells and the pilot test well;
- difficulty in obtaining reliable air flow measurements in the field; and
- time variability of vacuum/flow response of the subsurface.

Even with these sources of error, the predictions of equations (3) through (6) are an improvement over the assumption of a constant flow per well, independent of the number or spacing of wells in the system. The flow per well for the several multiple-well systems is significantly lower than the flow observed in the pilot test, consistent with design tool predictions. Assuming a constant flow per well in these cases would result in significant errors in sizing blowers and offgas treatment systems.

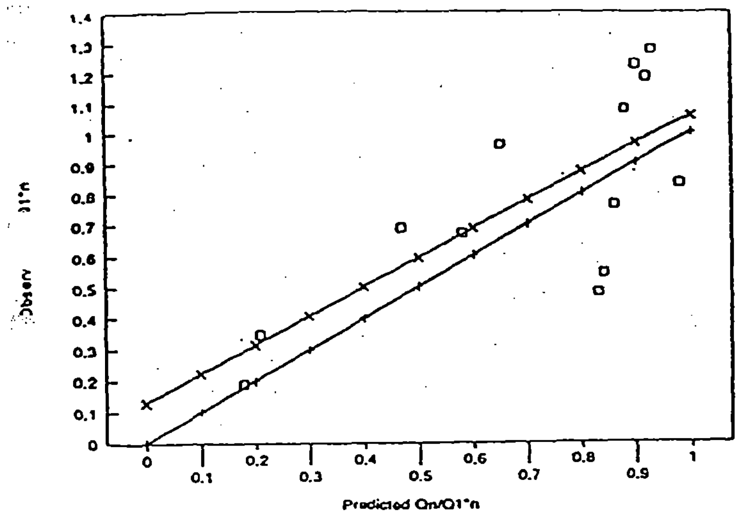

Figure 6

Comparison of observed and predicted ratio of system flow per well to single well flow for the operating sites listed in Table 1.

□ = data points

-x- = linear regression

-+- = theoretical line representing perfect agreement of observed and predicted

CONCLUSIONS

A design tool has been developed which estimates the performance of multiple-well soil vapor extraction systems based on a single-well pilot test. The product of the ground surface area between the wells and the air flux driven by subsurface vacuum yields an estimate of the total air flow rate per well. This facilitates more accurate estimates of blower sizing, offgas treatment selection, and well spacing requirements.

The design tool has been validated by comparing the observed performance of 13 operating multiple-well SVE systems with the predicted performance. The observed and predicted results generally agree, although substantial scatter is observed.

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ANALYSIS AND SCALEUP OF SOIL VAPOR EXTRACTION PILOT TEST DATA

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ABSTRACT

A set of equations has been developed which can facilitate design of effective SVE systems using data routinely obtained from conventional SVE pilot tests. The design tool can be used to estimate the effective cleanup radius, (defined as "the maximum distance from a vapor extraction point through which sufficient air is drawn to remove the required fraction of contamination in the desired time") for soil vapor extraction (SVE) systems. This provides an understanding of the contaminant recovery rate as a function of distance from each vapor extraction well and allows SVE systems to be designed so that cleanup goals can be achieved within a specified time frame.

The design tool can also facilitate the design of multiple-well SVE systems based on a single-well pilot test by accounting for the competition for air which occurs between vapor extraction wells in multiple-well SVE systems. Equations useful in designing horizontal SVE systems based on pilot tests performed on vertical wells are also developed by modifying and adapting the standard transport equations for a buried vertical rod and horizontal cable to represent vertical and horizontal SVE systems respectively. This approach facilitates more accurate estimates of blower sizing, offgas treatment selection, and well spacing requirements.

The design tool is based on simple models and uses analytical rather than numerical methods. It is simpler, faster, more versatile, and more robust then more sophisticated, multi-dimensional models. Although accuracy and resolution are somewhat reduced, the use of this model instead of more complicated approaches is generally justified given the limited site characterization data ordinarily available and the subsurface anisotropies commonly encountered at most small SVE sites.

Although widely applicable, the design tool should be used with some caution when the vadose zone is highly stratified or when venting contaminated soil greater than 30 feet below grade. This approach has been implemented in a proprietary computer program, VENT-ROI, which Groundwater Technology, Inc. has been using routinely since 1992 for rapid and effective design of SVE systems.

ANALYSIS AND SCALEUP OF SOIL VAPOR EXTRACTION PILOT TEST DATA

David H. Bass, Sc.D., CHMM

BACKGROUND

Soil vapor extraction (SVE) is a widely used *in situ* remediation technique for treatment of contaminated vadose zone soil. SVE removes volatile organic compounds (VOCs) from vadose zone soils by inducing air flow through contaminated areas. SVE is typically performed by applying a vacuum to either vertical or horizontal vapor extraction wells or to gravel-filled trenches. The resulting pressure gradient causes the soil gas to migrate through the soil pores toward the vacuum source. VOCs are volatilized and transported out of the subsurface by the migrating soil gas. In addition, SVE increases oxygen flow to contaminated areas, thus stimulating natural biodegradation of aerobically degradable contaminants.

SVE is applicable to most compounds with a vapor pressure greater than about 1 mm Hg at ambient temperature. This includes a wide variety of common contaminants, such as benzene, toluene, ethylbenzene, xylenes, gasoline hydrocarbons, mineral spirits, methyl t-butyl ether, tetrachloroethylene, trichloroethylene, and 1,1,1-trichloroethane. Since vapor pressure increases with temperature, SVE also can be applied to semi-volatile compounds by heating the vadose zone with steam or hot air.

The efficacy of a SVE system is determined by its ability to draw sufficient air through the contaminated portion of the vadose zone. Pilot tests are routinely performed to determine well spacing and to size components for full scale SVE systems, based on the attainable soil gas recovery rate and the attenuation of soil vacuum with distance from the vapor extraction well. Tests are typically performed on vertical, often pre-existing wells (see Figure 1); however the final system design may be modified in several ways so as to enhance the flow of air throughout the contamination zone:

- The system usually employs multiple wells, which compete with each other for air, resulting in a lower total soil gas recovery rate per vapor extraction well.

- The system may employ vertical wells screened over different intervals than the test well, in an effort to more closely match the vertical extent of soil contamination.

- Horizontally drilled wells may be used. These are usually installed near the bottom of the contaminated vadose zone, as depicted in Figure 2;

- Vented gravel-filled trenches (Figure 3), which typically extend downward to the bottom of the contaminated vadose zone, may be used. The gravel-filled portion of the trench is generally designed to match the vertical extent of contamination.

- Ambient air may be forced or allowed to be drawn through wells screened at the level of the vadose zone contamination.

- An engineered surface seal may be applied by paving or covering an unpaved surface with polyethylene film to prevent surface infiltration of air and water.

Historically, pilot test data were interpreted by defining the vapor extraction "radius of influence" as the distance from the vapor extraction well where an arbitrary vacuum level (usually 0.01 to 1 inch of water column) could be measured in the soil. Such rules of thumb yield no information on the quantity of air moving through the vadose zone, and so cannot provide an assessment of remediation time or design information specific to the contaminant (a system designed to remove benzene will be less effective on the less volatile xylene, for example). Furthermore, this approach provides no mechanism for scaling up from pilot test results for a single, vertical well to any of the above modifications which the final system design may employ. Without a theoretically-based method for assessing such scaleup issues, significant errors in well spacing, component sizing, and anticipated system performance can occur.

One approach to characterizing the subsurface in such a way as to facilitate the prediction of SVE system performance as a function of system geometry and orientation is the use of multi-dimensional analytical or numerical modeling of vacuum and soil gas flow fields in the vadose zone. Baehr, Marley, Falta, Lingineni, and others have employed such solutions for systems with unsealed or partially sealed surfaces.[1-4] Joss and Baehr have recently adapted MODFLOW, a groundwater numerical modeling program, to SVE applications.[5]

It is not always feasible to apply these sophisticated models, however. The data available at many small sites where SVE is considered, such as retail gasoline stations and dry cleaning facilities, are often sparse, and budgets rarely exist for gathering the more extensive data required for multi-dimensional models. Most of these sites have been repeatedly excavated and refilled, creating subsurface anisotropies which confound the limited data. Multi-dimensional models typically require substantial time and training to input variables and to run, making the design process tedious and costly. Therefore, the need exists for a design tool which can provide rapid order-of-magnitude assessments of SVE system performance, based on the limited data typically obtained from a routine SVE pilot study.

DESIGN TOOL DEVELOPMENT

The extent and rapidity of remediation in SVE systems is determined principally by the rate at which air which can be moved through the contaminated subsurface. Evaluation of the subsurface distribution of soil gas flow in response to an applied vacuum at the vapor extraction well is therefore the principal objective of SVE pilot test data analysis. The vacuum/flow response is a function of

1. factors affecting the permeability of the soil to air flow, including:
   - the resistance to flow provided by the soil matrix;
   - the resistance to air infiltration provided by the soil surface;

2. the geometric aspects of the vapor extraction well, such as:
   - screen length (in vertical and horizontal wells) or length of trench;
   - position of the screen or vented trench interval relative to ground surface;
   - horizontal vs vertical orientation;
   - well diameter or trench width; and

3. the number, spacing, and placement pattern of vapor extraction wells.

When a pilot test is performed, the geometric and placement aspects of the extraction well(s) are known. The only two variables left unspecified are the resistance to flow through the soil and the resistance to air infiltration through the ground surface. Therefore, only two parameters which are independent functions of these two variables need to be measured in order to describe air flow in the subsurface. In a conventional SVE pilot test, these parameters are (1) the soil gas recovery rate in response to an applied vacuum at the vapor extraction well and (2) the dissipation of vacuum with distance from the vapor extraction well(s).

With flow in the subsurface described, a conventional pilot test performed on a single, vertical well can be (1) sized so that the required extent of remediation is achieved in the desired time frame, (2) scaled up to multiple-well systems, and (3) scaled up to systems with differing extraction well geometries and/or orientations. The design tool described below has been derived to provide these capabilities. It assumes that the subsurface is homogeneous and isotropic within each vented stratum, and that the nature of surface does not change with distance from the vapor extraction well.

Ensuring the Required Extent of Remediation is Achieved in the Desired Time

In a single-well SVE system, the maximum distance from the vapor extraction well through which sufficient air is drawn to remove the required fraction of contamination in the desired time is the effective radius, R_E. This differs from the radius of influence, which is the distance from the vapor extraction well that vacuum can be detected. The effective radius is based on site-specific conditions and SVE system parameters, and it is specific to the contaminant, cleanup goals, and cleanup time frame.

The effective radius in a single-well SVE system will extend to the edge of the contaminant plume. All air entering the contamination zone is initially uncontaminated. As the air flows through the soil, contaminants rapidly equilibrate between soil and air phases.[6] This equilibration is determined by the contaminant soil concentration, vapor pressure, and water solubility, and by the moisture and organic content of the soil. Of these parameters, only the contaminant soil concentration changes dramatically during the course of the remediation, and so for a given site and contaminant, the equilibrium gas concentration can be expressed generally as a function only of soil concentration:

$$C_g = f(C_s) \tag{1}$$

where C_g = contaminant concentration in the gas
C_s = contaminant concentration in the soil

The rate at which contaminant mass is lost from soil must equal the rate at which the soil gas flowing through the soil carries the contamination away:

$$\frac{dM_s}{dt} = \frac{d(V_s C_s)}{dt} = C_g q = f(C_s)q \tag{2}$$

where M_s = mass rate of contaminant removal from soil
t = time
V_s = volume of soil (control volume)
q = flow rate of gas through control volume

The contaminated zone is represented as a uniform cylinder of radius R_E and height h, as indicated in Figure 4. Remediation will occur from the outside of the plume inward (due to lateral introduction of uncontaminated air into the contamination zone) and from the top down (due to vertical infiltration of air). Although the outermost portion of the contamination zone will be treated first, the rate of treatment at this location will be the slowest since the air flux decreases rapidly with distance from the vapor extraction well. The control volume is therefore taken as a fraction of the contamination zone furthest from the vapor extraction well, i.e. an annulus of outer radius R_E and inner radius ϵR_E. The value for parameter ϵ, typically 0.7 to 0.9, is selected such that vertical infiltration at distances less than ϵR_E from the vapor extraction well provides a rate of remediation roughly comparable to the remediation rate within the control volume due to lateral and vertical introduction of clean air. The control volume is then

$$V_s = \pi(R_E^2 - (\epsilon R_E)^2)h = (1 - \epsilon^2)\pi R_E^2 h \tag{3}$$

The gas flow through the control volume, q, is calculated by assuming that the driving force for infiltration of atmospheric air through the soil surface is the difference between the squares of the subsurface and atmospheric pressures.[2,6] At any distance r from the vapor extraction well, this driving force acts through an area of ground surface represented by an annulus of differential thickness:

$$dQ_v = k_v(P_a^2 - P_r^2)dA = k_v(P_a^2 - P_r^2)2\pi r dr \tag{4}$$

where Q_v = vertical infiltration of atmospheric air
r = distance from the vapor extraction well
P_a = absolute atmospheric pressure
P_r = absolute pressure at distance r from the vapor extraction well
k_v = constant
A = area of ground surface

The term $k_v(P_a^2 - P_r^2)$ comes from Darcy's Law for flow of a compressible fluid. The constant k_v is a lumped parameter related to the permeability of the soil to vertical gas infiltration, as well as to the gas viscosity, density, travel distance, and atmospheric pressure.

Since all the air collected at the SVE well must come ultimately from the atmosphere through the ground surface, the integral of equation (4) from the well radius to the radius of influence yields the rate of total soil gas recovery, Q^o:

$$\int_{r_w}^{R_I} dQ_v = 2\pi k_v \int_{r_w}^{R_I} (P_a^2 - P_r^2) r\,dr = Q^o \tag{5}$$

where r_w = radius of vapor extraction well
R_I = radius of influence

Rearranging equation (5) provides an expression for k_v. Substituting this into equation (4) and integrating from the well radius to the inner edge of the control volume gives:

$$\frac{Q_v}{Q^o} = \frac{\int_{r_w}^{\epsilon R_E} (P_a^2 - P_r^2) r\,dr}{\int_{r_w}^{R_I} (P_a^2 - P_r^2) r\,dr} \tag{6}$$

The gas passing through the control volume is the total gas flow collected less the vertical infiltration which occurs closer to the SVE well:

$$q = Q^o - Q_v = Q^o \frac{\int_{r_w}^{R_I} (P_a^2 - P_r^2) r\,dr - \int_{r_w}^{\epsilon R_E} (P_a^2 - P_r^2) r\,dr}{\int_{r_w}^{R_I} (P_a^2 - P_r^2) r\,dr} \tag{7}$$

Combining equations (2), (3), and (7) and integrating yields:

$$\int_{C_s}^{C_s^o} \frac{dC_s}{f(C_s)} = \frac{\int_{r_w}^{R_I} (P_a^2 - P_r^2) r\,dr - \int_{r_w}^{\epsilon R_E} (P_a^2 - P_r^2) r\,dr}{(1-\epsilon^2)\pi R_E^2 \int_{r_w}^{R_I} (P_a^2 - P_r^2) r\,dr} \frac{Q^o t}{h} \tag{8}$$

where C_s^o = initial contaminant concentration in the soil

Whenever $dC_s/f(C_s)$ and $P_r^2 rdr$ are analytically integrable, equation (8) provides a vehicle for relating the effective radius (R_E) to soil concentration in the control volume (C_s), soil gas recovery rate (Q^o), and remediation time (t) without the use of cumbersome numerical methods. Generally, r is assumed to be proportional either to $\log(P_r)$ or to $\exp\{P^2\}$.[6,7] At lower soil concentrations, it is proper to assume ideal partitioning between soil and gas ($f(C_s) = K_{gs}C_s$), while above a compound-specific threshold soil concentration, vapor concentration reaches the contaminant saturated vapor density, and $f(C_s)$ is constant.[8] When the contaminant is a diverse mixture of compounds, such as gasoline, $f(C_s)$ decreases exponentially with decreasing C_s over the course of the remediation.

Scaling Up to Multiple-Well Systems

When two or more vapor extraction wells are operated simultaneously, the subsurface air flow between the wells is decreased as the wells compete for air infiltrating from the surface. This reduces the effective radius between wells, as well as the flow per well in response to an applied vacuum.

The interwell effective radius, R_{EI}, is the distance from two vapor extraction wells to an equidistant point between them through which just enough air is drawn to remove the required fraction of contamination in the desired time. R_{EI} defines the remediation extent between vapor extraction wells and is always less than R_E, which defines the extent of remediation for a single-well system and for the area external to an array of vapor extraction wells. Quantifying R_{EI} requires only minor modifications to the equations from which R_E was derived above. The differential surface infiltration between two adjacent wells is given by equation (4). At a point located a distance R_{EI} from both wells, the differential volume through which this passes is $2\pi h R_{EI} dr$ (from equation (3)). Substituting these expressions for q and V_s in equation (2), and obtaining an expression for k_v from equation (5) yields

$$\int_{C_s^\circ}^{C_s} \frac{dC_s}{f(C_s)} = \frac{P_a^2 - P_r^2}{2\pi \int_{r_w}^{R_I} (P_a^2 - P_r^2) r dr} \frac{Q^\circ t}{h} \tag{9}$$

The approach to modeling total flow in multiple-well systems is developed below and is specific to hexagonal arrays. However, this approach can be extended readily to any conceivable well placement pattern. Relating multiple-well flow to pilot study results involves comparing the equations for the multiple-well system with the corresponding equation for single-well flow (Q^o) given in equation (4).

In SVE systems with three or more vapor extraction wells, the wells are usually placed so that the lines connecting the well form approximately equilateral triangles, as shown in Figure 5. In this case, the capture zone for each well is bounded by two to six lines representing the locus of points equidistant from each pair of adjacent wells. These lines intersect at 120° angles (Figure 5), and when sufficient wells are present, form an array of regular hexagons (Figure 6).

To model the system depicted in Figure 5 which has three equally spaced wells, assume that air infiltrating the ground surface migrates to the vapor extraction well nearest the point of infiltration. As shown at the top of Figure 5, infiltration will be the same for each well as for the single-well system, so long as $r \leq R$ (where **R** is half the well spacing). When $R < r < 2R/\sqrt{3}$, the area available for surface infiltration is reduced by the fraction $2\Theta_r/\pi$, as depicted in the lower right of Figure 5. The lower left of Figure 5 shows that when $r \geq 2R/\sqrt{3}$, the area available for surface infiltration is reduced by the fraction $1/6 + \Theta_r/\pi$. The relative flow per well for a three-well and single-well system, assuming identical well construction and applied vacuum, is then:

$$\frac{Q_{3,array}}{Q^\circ} = \frac{\int_{r_w}^{R}(P_r^2-P_a^2)rdr}{\int_{r_w}^{R_I}(P_r^2-P_a^2)rdr} + \frac{\int_{R}^{2R/\sqrt{3}}(P_r^2-P_a^2)(1-\frac{2\theta_r}{\pi})rdr}{\int_{r_w}^{R_I}(P_r^2-P_a^2)rdr} + \frac{\int_{2R/\sqrt{3}}^{R_I}(P_r^2-P_a^2)(\frac{5}{6}-\frac{\theta_r}{\pi})rdr}{\int_{r_w}^{R_I}(P_r^2-P_a^2)rdr} \tag{10}$$

where $Q_{3,array}$ = flow per well from a three-well triangular system

Extending this analysis to a hexagonal array of n vapor extraction wells spaced 2R feet apart requires classification of vapor extraction wells as either interior or exterior. Interior wells are adjacent to six other wells, exterior wells are adjacent to fewer than six (the seven-well array in Figure 6 has one interior and six exterior vapor extraction wells). The distinction is important because interior wells are assumed to have no influence beyond a distance of $2R/\sqrt{3}$. The general expression for the relative flow per well for a hexagonal array of n wells and a single-well system is:

$$\frac{Q_{n,array}}{Q^\circ} = \frac{\int_{r_w}^{R}(P_r^2-P_a^2)rdr}{\int_{r_w}^{R_I}(P_r^2-P_a^2)rdr} + \frac{\int_{R}^{2R/\sqrt{3}}(P_r^2-P_a^2)(1-\frac{(6n-2n_e-6)\theta_r}{n\pi})rdr}{\int_{r_w}^{R_I}(P_r^2-P_a^2)rdr} + \frac{\frac{n_e}{n}\int_{2R/\sqrt{3}}^{R_I}(P_r^2-P_a^2)(\frac{n_e+2}{2n_e}-\frac{\theta_r}{\pi})rdr}{\int_{r_w}^{R_I}(P_r^2-P_a^2)rdr} \tag{11}$$

where $Q_{n,array}$ = flow per well from an n-well array of vapor extraction wells
n_e = number of exterior vapor extraction wells

Equation (11) has been validated by comparing the observed performance of 13 operating multiple-well SVE systems with the predicted performance, based on single-well pilot tests.[9] The observed and predicted results generally agreed, although substantial scatter was observed.

Scaling Up to Systems with Differing Geometries and Orientations

Equations describing the flux resulting from a potential applied to buried objects in heat transfer applications are available in standard transport texts. The potential in the case of heat transfer is the temperature difference between the buried object (generally assumed to be of uniform temperature) and the ground surface; the resultant flow is the net heat transferred to or from the buried object. The potential in SVE applications is the difference between the square of the pressures at the vapor extraction well/trench and the ground surface (atmospheric);[2,6] the resultant flow is the soil gas extraction rate. Note that this approach implies that the pressure within the vapor extraction well/trench is uniform. This is ordinarily a good assumption, however substantial pressure drop can occur over long lengths of perforated pipe, especially at higher air flow rates and smaller pipe diameters. A method for estimating vacuum distribution along perforated pipes in soil vapor extraction applications was presented in an earlier publication.[10]

The equation for transport to/from a thin vertical rod buried from the ground surface to a depth N is represented by the following equation:[11]

$$Q_v = \frac{2\pi k N \phi}{\ln(4N/D)} \tag{12}$$

where Q_v = resultant flow (soil gas recovery rate)
ϕ = applied potential ($P_{SVE}^2 - P_{atm}^2$)
D = diameter of the rod

The transport to/from a thin vertical rod buried from a depth N_1 to a depth N_2 can be found by subtracting the transport to/from a rod buried from the surface to N_1 from the transport to/from a rod buried from the surface to N_2:

$$Q_v = 2\pi k \phi \left(\frac{N_2 \ln(4N_1/D) - N_1 \ln(4N_2/D)}{\ln(4N_2/D)\,\ln(4N_1/D)} \right) \tag{13}$$

The transport (neglecting end effects) to/from a horizontal rod of length L buried at a depth N from the ground surface can be determined from:[11]

$$Q_h = \frac{2\pi k L \phi}{\ln[(2N/D) + \sqrt{(2N/D)^2 - 1}]} \tag{14}$$

Equation (13) provides the flow response to a vacuum applied to a vertical vapor extraction well of diameter D screened from depth N_1 to depth N_2; equation (14) provides the flow response to a vacuum applied to a horizontal well of screen length L and diameter D installed at a depth N below the surface. A vented trench which is much deeper than it is wide can be represented by the equation for transport to/from a buried vertical sheet. In practice, however, the width and depth of vented trenches are almost always similar (since trenches are used almost exclusively for shallow SVE applications), and equation (14) can be used to represent the trench with D taken to be the effective diameter of the trench, D_{eff}:

$$D_{eff} = 2\sqrt{wh/\pi} \tag{15}$$

where w = width of the trench
h = thickness of gravel-filled portion of the trench

If a conventional pilot test has been performed, equations (13) and (14) can be used to predict the vacuum/flow response for SVE systems of geometries which differ from the pilot test well/trench. For example, by dividing equation (14) by equation (13), the results of a pilot test performed on a vertical well (diameter D_v, screened from N_{v1} to N_{v2} below grade) can be extrapolated to a horizontal well (diameter D_h, length L, installed at a depth N_h below the surface):

$$\frac{Q_h}{Q_v} = \frac{\phi_h}{\phi_v}\left(\frac{\ln(4N_{v2}/D_v)\ \ln(4N_{v1}/D_v)}{N_v \ln(4N_{v1}/D_v) - N_{v1}\ln(4N_{v2}/D_v)}\right)\left(\frac{L}{\ln[(2N_h/D_h) + \sqrt{(2N_h/D_h)^2 - 1}]}\right) \tag{16}$$

where Q_h = soil gas flow collected by horizontal well
Q_v = soil gas flow collected by vertical well in the pilot test
ϕ_h = vacuum applied to horizontal well
ϕ_v = vacuum applied to vertical well in the pilot test

Similarly, the performance of vertical and horizontal wells of various diameters and screened intervals also can be assessed. The validity of equation (16) has been demonstrated in case studies in which conventional vertical pilot tests were scaled up to horizontally drilled wells and to vented trenches.[12]

This approach assumes that the horizontal and vertical air permeability of the soil matrix are comparable, a condition which is not always met in stratified formations. If the ratio of the horizontal and vertical permeabilities, k_h/k_v, is known, compensating for differing horizontal and vertical permeabilities requires multiplying all values for depth below grade by this ratio. For example, equation (16) would become

$$\frac{Q_h}{Q_v} = \frac{\phi_h}{\phi_v}\left(\frac{\ln(4kN_{v2}/D_v)\ \ln(4kN_{v1}/D_v)}{kN_{v2}\ln(4kN_{v1}/D_v) - kN_{v1}\ln(4kN_{v2}/D_v)}\right)\left(\frac{L}{\ln[(2kN_h/D_h) + \sqrt{(2kN_h/D_h)^2 - 1}]}\right) \tag{17}$$

where k = k_h/k_v

DISCUSSION

The equations derived above provide a basis for design of effective SVE systems based on data routinely obtained from conventional SVE pilot tests. Examination of these equations lead to some conclusions regarding SVE design which are not immediately obvious.

Equations (8) and (9) indicate that for a fixed cleanup level, changes in vapor extraction rate (Q^o), cleanup time (t), and depth of the vented interval (h) will not effect the effective radius so long as $Q^o t/h$ remains constant. In other words, the same system performance can be obtained in half the time by doubling the vapor extraction rate or halving the depth of the vented interval.

Figure 7 shows an example of how single-well effective radius varies with $Q^o t/h$ for a variety of common volatile soil contaminants (where cleanup is defined as 90% removal; ideal soil-vapor partitioning and an unsealed surface are assumed). The conditions in this example are typical for SVE systems, and the resulting effective radius varies from a few feet to as much as 70 feet. Effective radius is most sensitive to the volatility of the contaminant; the effective radius for weathered gasoline is 3 to 10 times less than for 1,1,1-trichloroethane under the same conditions. Large changes in $Q^o t/h$ are required to substantially affect effective radius, especially for the more volatile contaminants; doubling the effective radius generally requires increasing $Q^o t/h$ by a factor of 10 to 50.

The above derivation distinguishes between the single-well effective radius, R_E, and the interwell effective radius, R_{EI}. Since R_{EI} is always less than R_E, an optimum SVE system design often will place vapor extraction wells closer to each other than to the edge of the plume. In other words, bunching vapor extraction wells in the middle of the site often provides more uniform remediation than distributing well evenly throughout the site. In extreme cases where horizontal permeability greatly exceeds vertical permeability, timely remediation between wells is not possible without air injection, regardless of well spacing.

Equation (11) indicates that, for a given applied vacuum and vapor extraction well construction, the flow per well in a multiple-well system is always less than flow in a single-well system. This difference can be dramatic, depending on the well spacing and relative horizontal-to-vertical permeability. Neglecting the competition for air between wells in multiple-well systems will therefore result in unnecessary costs due to oversized vapor extraction blowers and offgas treatment technology.

LIMITATIONS

While the above discussion provides the basis for a useful design tool, it is not applicable to all SVE situations without qualification. The simplifying assumptions which provide the ease of calculation also contribute to the uncertainty in the result. For example, the actual resistance to air flow provided by the soil matrix may be non-uniform due to subsurface anisotropies and anthropogenic structures (sewers, foundations, etc.). Unfortunately, site data are often inadequate to characterize fully such features. This design tool may be useful as a basis for design, but SVE installations must be executed with sufficient flexibility to enable compensation for such unidentified features.

This derivation is applicable to SVE systems with any well construction, number of wells, or well orientation. While it presumes an unsealed surface, it can be readily extended to sites with an engineered surface seal. However, because it assumes the vadose zone conditions to be uniform with depth, caution should be exercised when applying this model to SVE systems venting strata greater than about 30 feet below grade. In addition, this design tool is not appropriate when vertical infiltration of air through the ground surface is virtually non-existent. Such a situation would arise during venting of a high permeability stratum underlying an extensive, substantial, and continuous stratum of much lower permeability. Fortunately, such situations occur only rarely, and they can be modeled effectively using the sealed surface approach taken by Johnson, et al.[6,13]

CONCLUSIONS

A set of equations has been developed which can facilitate design of effective SVE systems using data routinely obtained from conventional SVE pilot tests. This approach can be used to (1) estimate the effective cleanup radius; (2) design multiple-well SVE systems based on a single-well pilot test; and (3) design horizontal SVE systems based on pilot tests performed on vertical wells. The design tool facilitates more accurate estimates of blower sizing, offgas treatment selection, and well spacing requirements.

The design tool is based on a simple model which uses analytical rather than numerical methods, and so is simpler, faster, more versatile, and more robust then more sophisticated, multi-dimensional models. Although accuracy and resolution are somewhat reduced, the use of this model instead of more complicated approaches is generally justified given the limited site characterization data ordinarily available and the subsurface anisotropies commonly encountered at most small SVE sites.

Although widely applicable, the design tool should be used with some caution when the vadose zone is highly stratified or when venting contaminated soil greater than 30 feet below grade. This approach has been implemented in a proprietary computer program, VENT-ROI, which Groundwater Technology, Inc. has been using routinely since 1992 for rapid and effective design of SVE systems.

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FIGURE 1

TYPICAL VERTICAL IN-SITU SOIL VAPOR EXTRACTION DESIGN

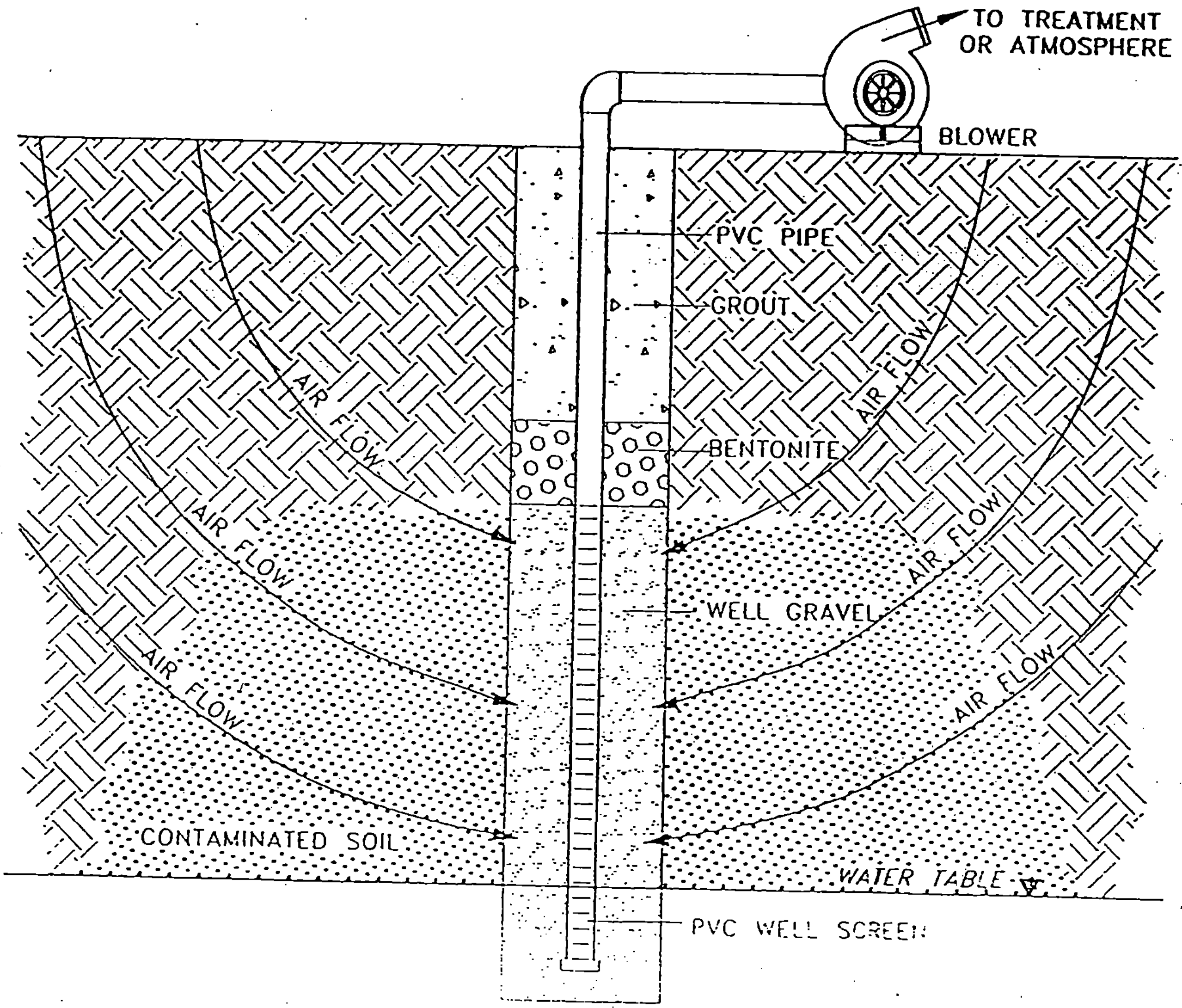


FIGURE 2

TYPICAL HORIZONTALLY DRILLED SOIL VAPOR EXTRACTION WELL

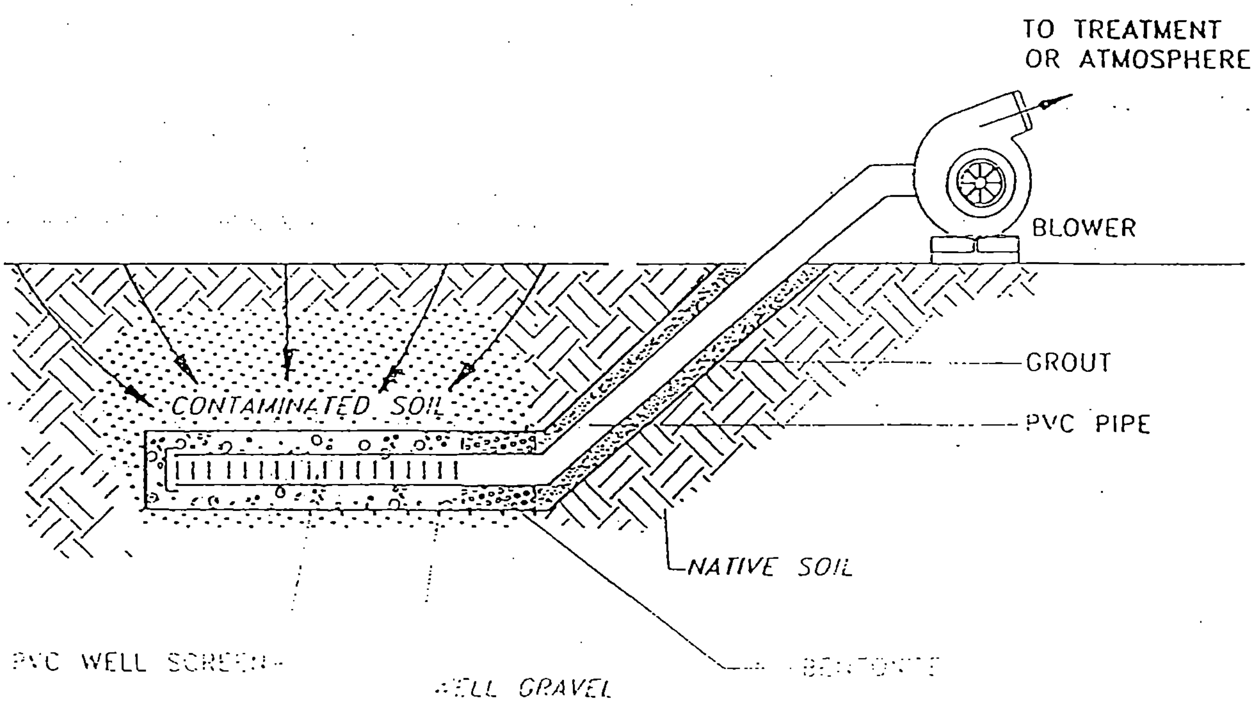
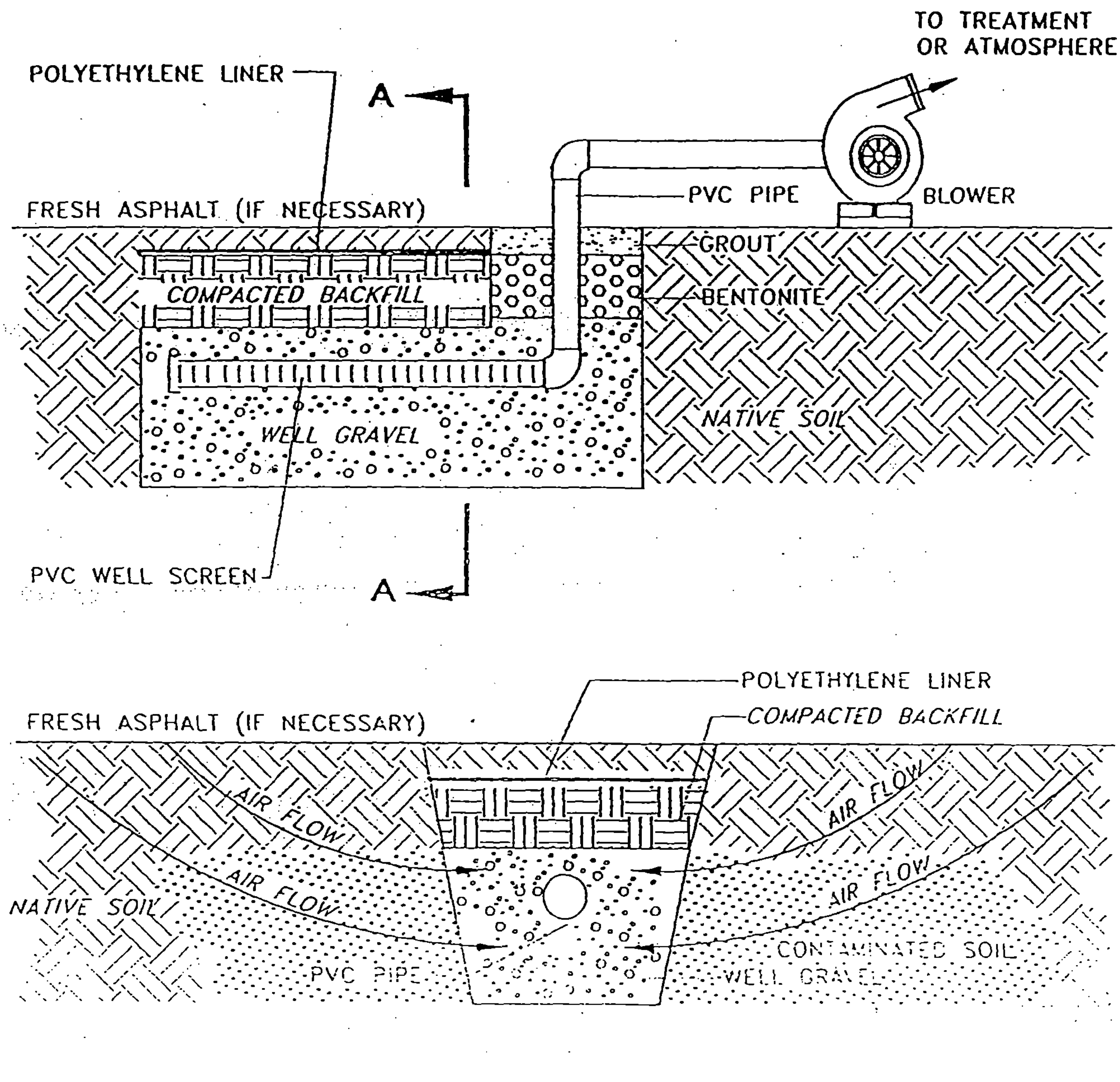


FIGURE 3

TYPICAL HORIZONTAL IN-SITU SOIL VAPOR EXTRACTION DESIGN



TRENCH CROSS-SECTION A-A

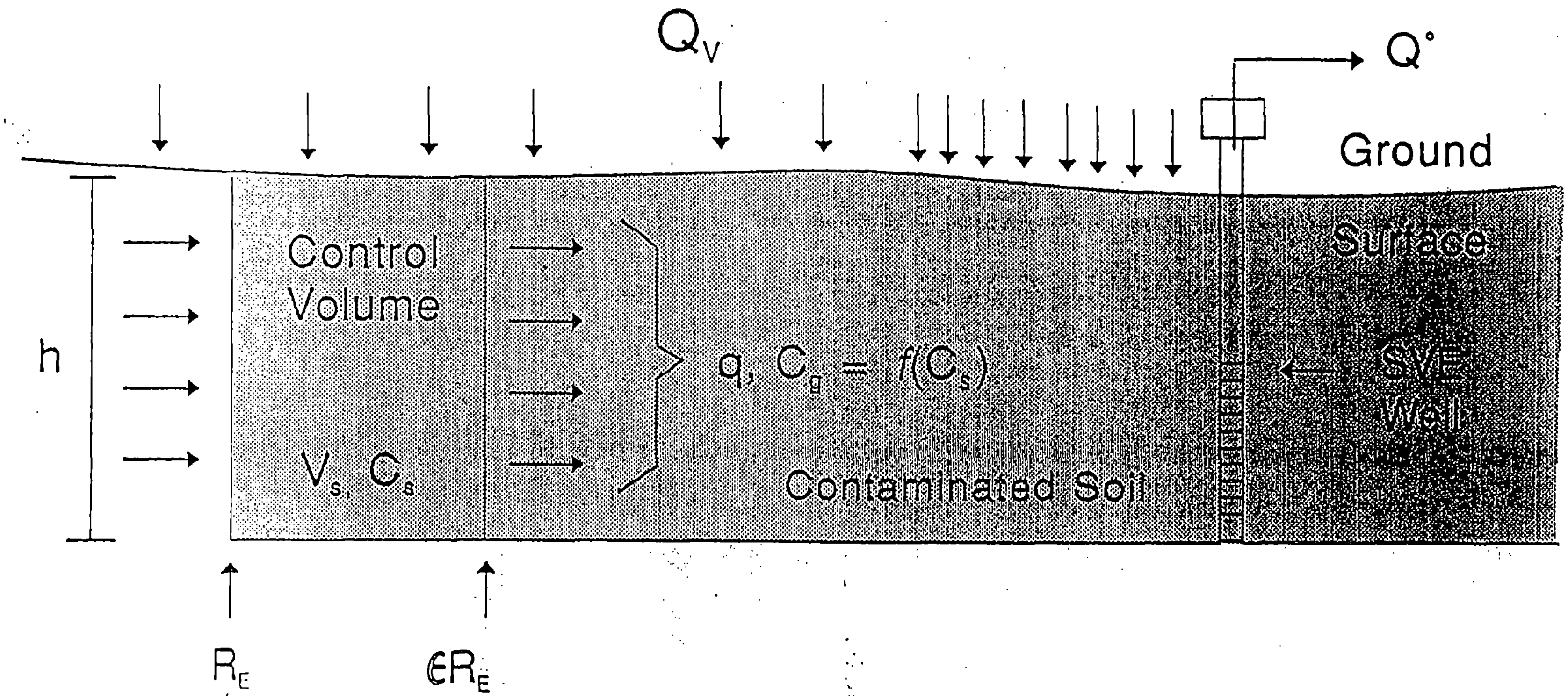


Figure 4: Conceptualization of the model. The system is to be designed such that the effective radius, R_E, corresponds to the extent of contamination. Clean air enters the contaminated zone by horizontal movement through the soil and by vertical infiltration through the ground surface. The overall cleanup time is dominated by the remediation rate for the contaminated soil between ϵR_E and R_E ("control volume"), which is determined by the air flow rate, q, through this portion of the contaminated zone.

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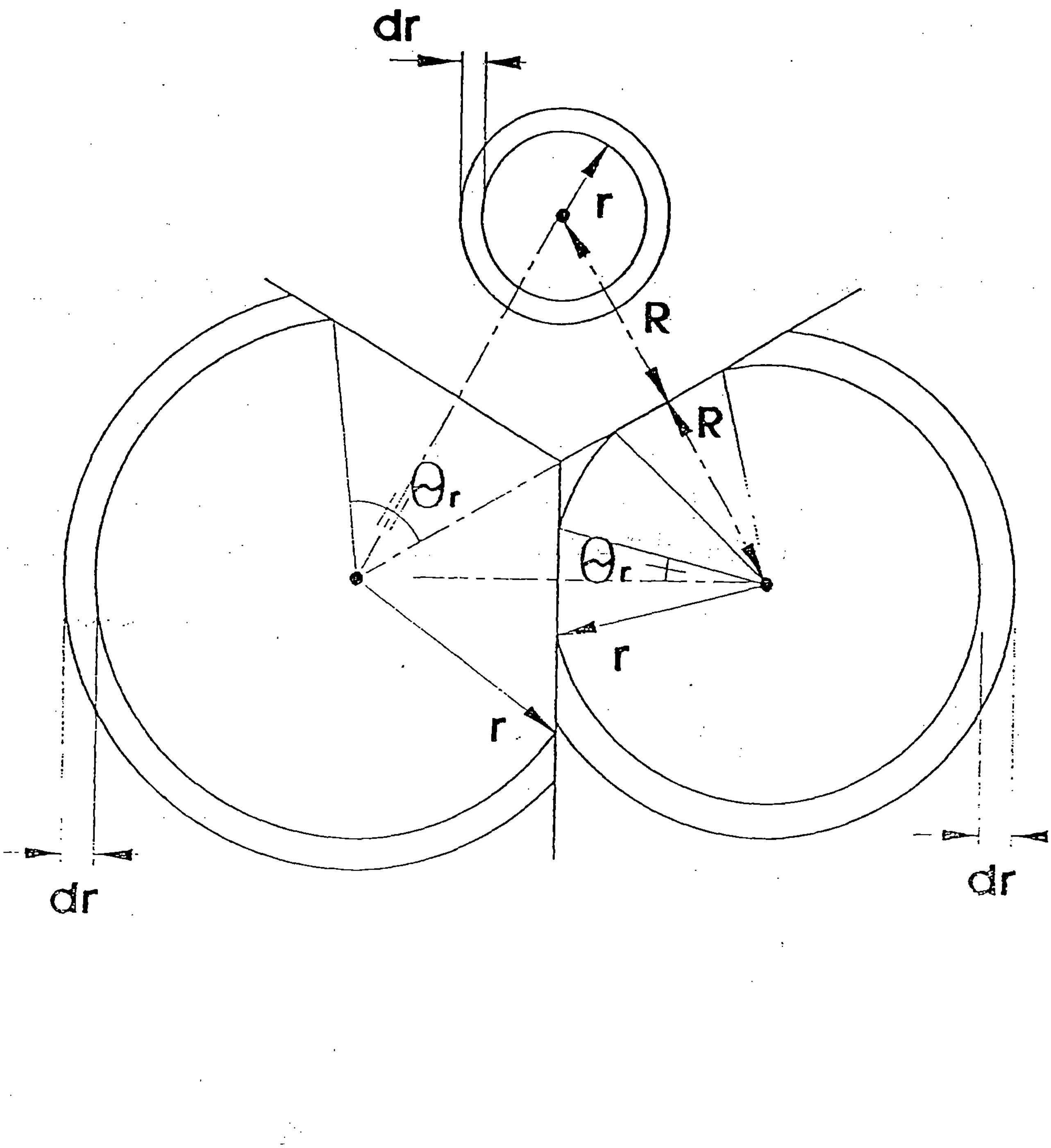
FIGURE 5

Modeling competition for air infiltrating the ground surface between three vapor extraction wells (.), placed in an equilateral triangle with spacing 2R. The capture zone for each well is bounded by the locus of points equidistant from each pair of adjacent wells.

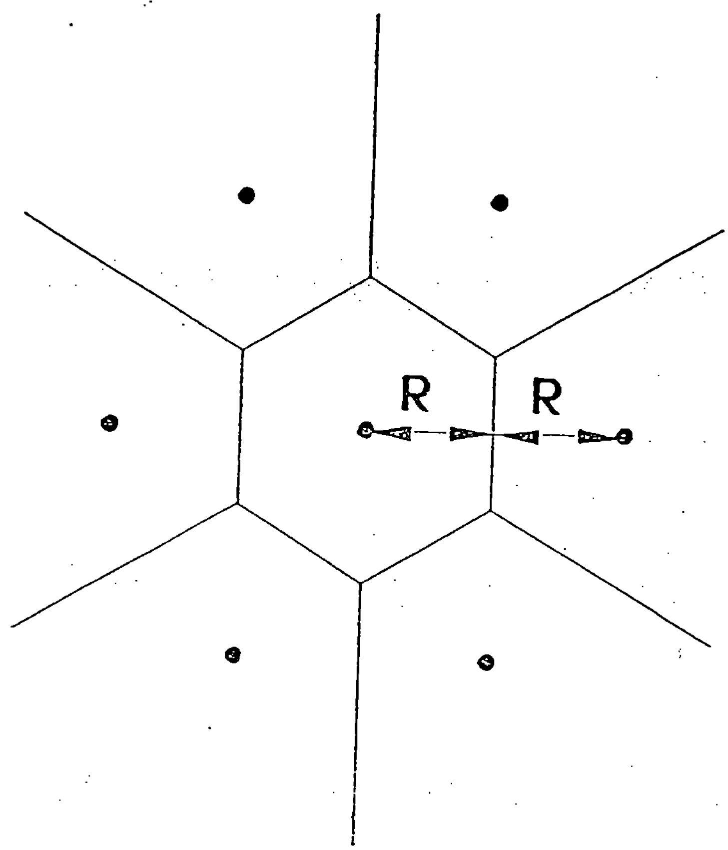


KEY

● – VAPOR EXTRACTION WELL

FIGURE 6

A Hexagonal Array of Seven Vapor Extraction Wells



KEY

● – VAPOR EXTRACTION WELL

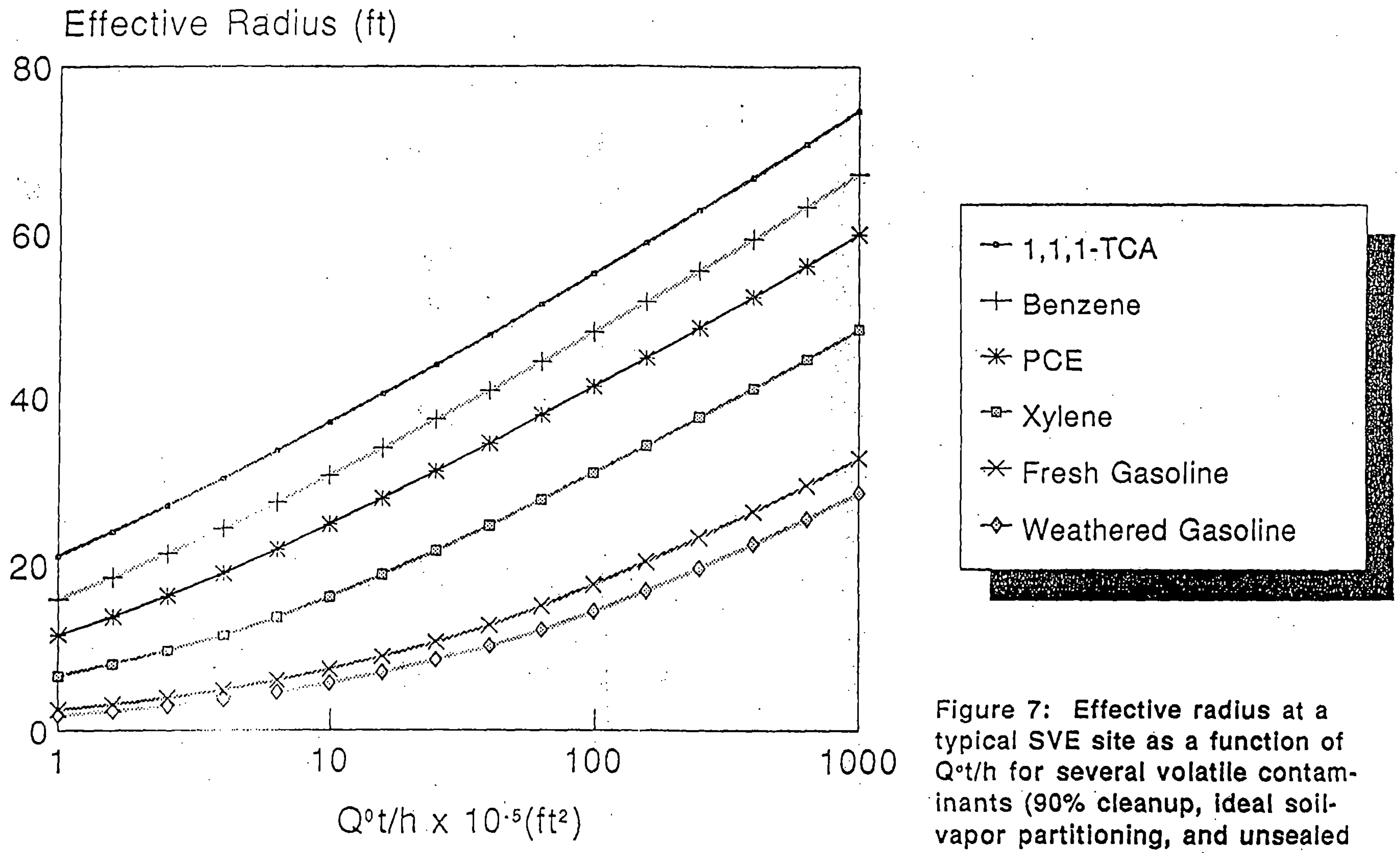


Figure 7: Effective radius at a typical SVE site as a function of Q°t/h for several volatile contaminants (90% cleanup, ideal soil-vapor partitioning, and unsealed surface assumed).

P:\WENSKEVI\HGDATA\BASS\FIG4A

STATE FIRE MARSHALL
SITE FEATURE SCORING SYSTEM (SFSS) CHART

SFM SITE FEATURE SCORING SYSTEM (SFSS) CHART
(USE "SFSS GUIDELINES" TO COMPLETE THIS CHART)

I. OWNERSHIP OF TANKS	II. LOCATION OF TANKS
Wheeling-Pittsburgh Steel Corporation Martins Ferry Plant Martins Ferry, Ohio	See attached Figures 1 and 3

	COLUMN A		COLUMN B		COLUMN C		COLUMN D	
Site Features	Score 20	Enter Score	Score 15	Enter Score	Score 10	Enter Score	Score 5	Enter Score
1. Distance of UST system from closest potable-water supply source currently in use is:	> 1000 ft.		300 - 1000 ft.	15	< 300 ft.		Inside of designated sensitive area	
2. Depth to groundwater is:	> 50 ft.		31 - 50 ft.	15	15 - 30 ft. or unknown		< 15 ft.	
3. Predominant soil type of substratum is:	Clay or shale		Silt or clayey sands or fine sandstone		Silty sand or fine sand, unknown, or sandstone		Clean sand, gravel, or conglomerate	5
4. Natural and/or man-made conduits or receptors -- See Worksheet Below	< 8	20	8 - 10		11 - 13		> 13	
Subtotals:		20		30				5
							TOTAL SCORE (SUBTOTALS)	55

SITE FEATURE 4 WORKSHEET:

Basements or subsurface foundations within 100 feet of UST system	4 points	0
Storm sewer within 50 feet of UST system	4 points	0
Sanitary sewer within 50 feet of UST system	4 points	0
Septic system leach field within 50 feet of UST system	2 points	0
Water line main within 50 feet of UST system	1 points	0
Natural gas line main within 50 feet of UST system	1 points	0
Bedrock area prone to dissolution along joints of fractures within 100 feet of UST system	1 points	0
Faults or known fractures within 100 feet of UST system	1 points	0
Buried telephone/television cable main within 50 feet of UST system	1 points	0
Buried electrical cable within 50 feet of UST system	1 points	0
	TOTAL POINTS	0

CONSTITUENT	CATEGORY 1	CATEGORY 2	CATEGORY 3	CATEGORY 4
TOTAL SCORE	< 31	31-50	51-70	> 71
Soil BTEX	.006/4/6/28	.170/7/10/47	.335/9/14/67	.500/12/18/85
Groundwater BTEX	.005/1/.700/10	.005/1/.700/10	.005/1/.700/10	.005/1/.700/10
Soil TPH (Gasoline)	105	300	450	600
Soil TPH (Others)	380	642	904	1156